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THESIS

EXPERIMENTAL EVALUATION OF A LOW COST ACOUSTIC COMMUNICATION SYSTEM FOR AUVs

by

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EXPERIMENTAL EVALUATION OF A LOW COST ACOUSTIC COMMUNICATION SYSTEM FOR AUVs

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Submitted in partial fulfillment
of the requirements for the degree of

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ABSTRACT

As the Navy has refocused its goals towards littoral warfare, mine countermeasures have become an area of special interest. The Naval Postgraduate School is developing an autonomous underwater vehicle to map shallow water minefields--a vital role in the Navy's overall plan for mine countermeasures. A key feature of the vehicle is its low cost, and to this end it uses a commercially available system called "DiveTracker" for precise acoustic navigation and communication. This research experimentally evaluated the reliability of the DiveTracker communication system in conditions approximating those for which the vehicle is designed. It was concluded that highly reliable communication of short commands will be restricted to relatively short separation distances between nodes. The very shallow water acoustic channel is highly variant in both signal attenuation and background noise levels. The maximum range is limited by the background noise while the probability of correct message reception depends on the received signal to noise ratio. Initial data indicates that the low cost unit under development cannot communicate beyond 500 meters with a probability of a single roundtrip success greater than 34 percent. Several options are available for its improvement.

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I. INTRODUCTION

A. BACKGROUND ON MINE COUNTERMEASURES

1. Historical Perspective

Especially today when compared with modern warships and weapons technology, and throughout naval history, mine warfare and mine countermeasures have been a somewhat less glamorous aspect of the profession. The threat imposed by mines has often been overlooked by naval leadership. As a consequence, enemies have periodically been able to use them to great advantage. When this happens there is typically a reactionary increased emphasis on the field and the methods and technology comprising mine countermeasures improves. Once they do improve, however, the field is again typically left to fade into the background until brought to the forefront at some later date by yet another incident.

The Persian Gulf War was such an incident. Mines made civilian and military ships alike vulnerable, stopped the "Fast Sealift" ships from delivering essential materiel, and prevented a Marine landing on the coast of Kuwait. They have damaged at great cost USS *Samuel B. Roberts*, USS *Tripoli* and USS *Princeton*. It has thus again become clear that the mine problem reaches farther than the ships it directly threatens; it disrupts our ability to support a land campaign by preventing essential materiel from being delivered in timely fashion.

Numerous shortfalls in the way mine clearance operations were conducted were identified during the War, along with some preliminary requisite solutions [Pearson]. The Navy has since refocused its attention and in fact committed itself to being proactive about the business of mine countermeasures for the indefinite future [Boorda], and taken some initial steps. This is especially appropriate in light of the organization's relatively recent focus on the littorals and regional conflicts that may well involve third-world countries--countries that might find mine warfare particularly attractive. In fact, there has been speculation that recognition of the effectiveness of mines in the Persian Gulf War is the reason behind the dramatic increase in their production in the worldwide arms market; the number of countries producing mines for sale has recently gone up forty percent [Connelly]. Such mines are available to anyone willing to pay a very reasonable price. It is easy to see why the mine threat is one that is only likely to increase.

2. Current Efforts

In a white paper issued in December of last year, the late Chief of Naval Operations called for mine countermeasures to become an integral part of naval force doctrine, education and training. He directed that a

"Campaign Plan" be developed to solve near-term shortfalls and also begin the integration of organic mine countermeasures into the Fleet [Boorda].

The new Mine Countermeasures Concept of Operations, as explained by the Mine Warfare Branch under the Chief of Naval Operations, consists of four parts:

- mapping, survey and intelligence operations
- surveillance operations
- organic mine countermeasures operations
- dedicated mine countermeasures operations

Mapping, survey and intelligence operations are aimed at constructing a database of currently existing mines and mine-like objects in harbors and key locations around the world. *Surveillance operations* begin when international tensions first begin to rise, so that it may be determined if and where a potential adversary might employ mine warfare. *Organic mine countermeasures* would enable naval forces on the scene to locate and clear mines as required "in stride" using immediately available assets. *Dedicated mine countermeasures operations* would then be carried out by specialized naval forces, for example, mine countermeasures ships. These forces are and will remain limited in number, would presumably conduct any volume clearance operations in areas where control of the battlespace was ensured, but would take some time to reach the scene.

In support of the latter two parts of this concept, and perhaps additionally the first, is the development of undersea vehicles that can accurately map a minefield, pinpointing mine locations for later destruction or neutralization. (In fact, the ability to locate and quickly clear mines in shallow and very shallow water, including a so called "surf zone capability," was a critical need identified in the Gulf War [Pearson].) Using such undersea vehicles obviates the need for any human to go in harm's way, be it on a helicopter, mine countermeasures ship or underwater as a swimmer. They also have the advantage of operating in a relatively clandestine fashion, and thus are not obvious to any observing enemy during the critical phase prior to force commitment.

Following the development of the DARPA/DRAPER UUV, now recently completing the advanced minehunting and mapping program (AMMT), two such vehicles are presently being tested by the Navy for submarine launch. These are the NMRS or "Near Term Mine Reconnaissance System" and the RMS or "Remote Minehunting System." The NMRS is a tethered underwater vehicle launched from a submarine's torpedo tube. Any such vehicle has numerous obvious disadvantages associated with its tether. The proposed long term solution is a relatively expensive untethered version, also exclusively submarine launched.

The RMS is a "dolphin" vehicle that uses an air breathing diesel engine for propulsion. As a result it has excellent range, but must operate primarily near the surface. It tows a minehunting sonar. Because of its relatively large size, it must be launched from a sizable surface ship, which diminishes the inherent clandestine advantage of such a vehicle. Additionally, since the sensor sled is towed behind, the vehicle's own protection is not assured.

For the past eight years the Naval Postgraduate School has, in an interdepartmental effort aimed at building autonomous control technology, built and tested two of its own autonomous underwater vehicles that have had as their design mission the mapping of shallow water minefields (10 to 40 feet water depth). The latest of these two "Phoenix" vehicles currently serves as the testbed for the research work of a team of about ten to fifteen faculty and student researchers.

B. THESIS OBJECTIVES AND STRUCTURE

As part of the NPS AUV research project, the objectives of this study were to investigate the reliability of intervehicle communications--such as would be needed for vehicle control purposes--using a commercially available navigation and communication system called "DiveTracker." This was done through an experimental evaluation of very shallow water acoustic communications in the Monterey Bay waters both inside and outside the harbor area. The primary variable was the distance between units while probability of message transmission was calculated on the basis of 100 identical message repeats.

Structurally, with some background now in the business of mine countermeasures, Chapter II of this thesis moves ahead to provide a brief description of *Phoenix*. Chapter III follows with a detailed discussion of the components (hardware and software) that make up the *DiveTracker* acoustic navigation and communication system used on the *Phoenix*. Chapter IV provides a review of underwater acoustics as they relate to the communication problem and gives a cursory review of current related research. Chapter V gives an in-depth idea of how the *DiveTracker* communication function is actually accomplished. With the groundwork laid, Chapter VI presents the experimental data and the methods used to obtain it, along with analysis. Chapter VII gives some idea about how the data may be interpreted from a probability point of view. Conclusions and recommendations for further study comprise Chapter VIII.

II. NPS PHOENIX AUV

A. MECHANICAL DESCRIPTION

Phoenix is a relatively small vehicle of about two meters in length, with a rectangular aluminum mid-body approximately ten inches vertically and sixteen inches horizontally. Submerged it displaces 385 pounds and with the flooded nose is effectively 435 pounds in mass. External and internal views are shown in Figures (1) and (2) respectively.

Power is provided by two lead acid gel cell battery packs. One of these provides power to propulsion and thrusters, the second serves computers and gyros.

Propulsion is provided by two direct drive DC electric motors driving two standard counter-rotating screws. Maneuvering and station-keeping is further facilitated by fore and aft vertical and cross-body thrusters (total of four) housed in tunnels of three inches in diameter. A pair of bow planes and a pair of stern planes together with pairs of forward and aft rudders provide ample control surfaces that further enhance maneuverability.

The vehicle's primary external environment sensors are two relatively inexpensive, commercially available sonars: a Tritech ST1000 Profiler and a Tritech ST725 Scanning Sonar. Both are mounted behind and protrude through a flooded fiberglass nose cone and are controlled by an onboard computer. With a narrow beam width (24° by 1°, mechanically scanned) the ST1000 is used primarily for vehicle motion control meaning, for example, hovering and positioning around an object, and for object identification. The ST725 has a much larger beam width for larger area scanning.

B. SOFTWARE ARCHITECTURE

Overall the vehicle's software uses a "tri-level control" architecture that is based on the watchstanding organization of a Navy submarine underway. The *Strategic Level* is like the Commanding Officer, generating mission code. At this level the user programs the vehicle for a specific mission. The *Tactical Level* is likened to the Officer of the Deck, communicating with the Commanding Officer and then carrying out tactical processes such as navigation and sonar operation. The *Execution Level* is at the lowest level, similar to the individual watchstanders on a submarine, responding to orders from the Tactical Level and controlling specific hardware (like thrusters and screws) to get the job done.

Other detailed software routines within the above structure include those for sonar classification and obstacle avoidance, obviously critical parts in enabling the vehicle to perform its mission. A navigation system employing a multi-mode Kalman filter allows the integration of the acoustic navigation system (*DiveTracker*) with deadreckoning and differential or standard GPS as available when surfaced. This system operates at an update rate of about ten hertz and interfaces at the Execution level, while Tactical and Strategic Level processes run asynchronously [Healey et al, 1995].

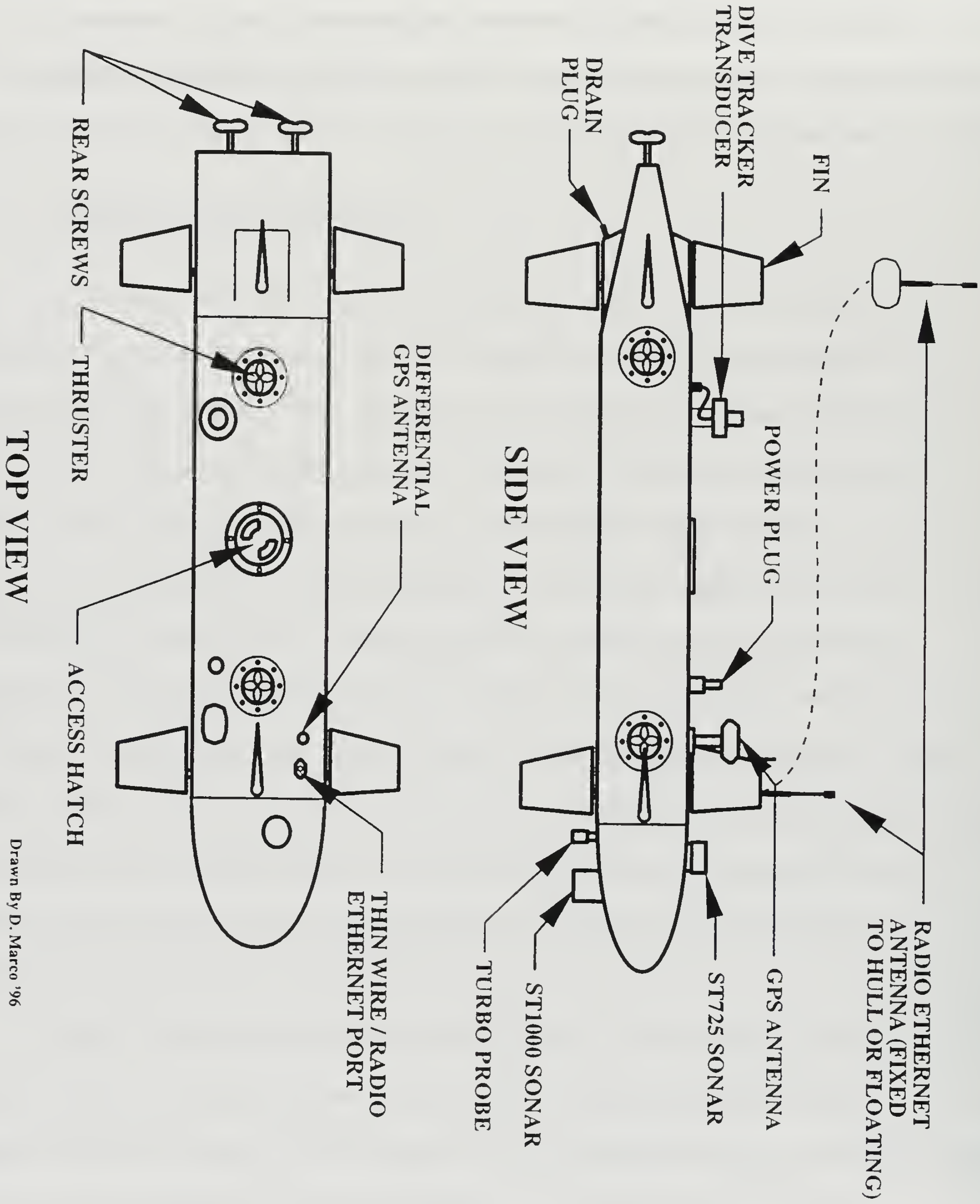

Figure 1. External Views of *Phoenix* AUV. *DiveTracker* transducer is mounted on the top. From [Marco].

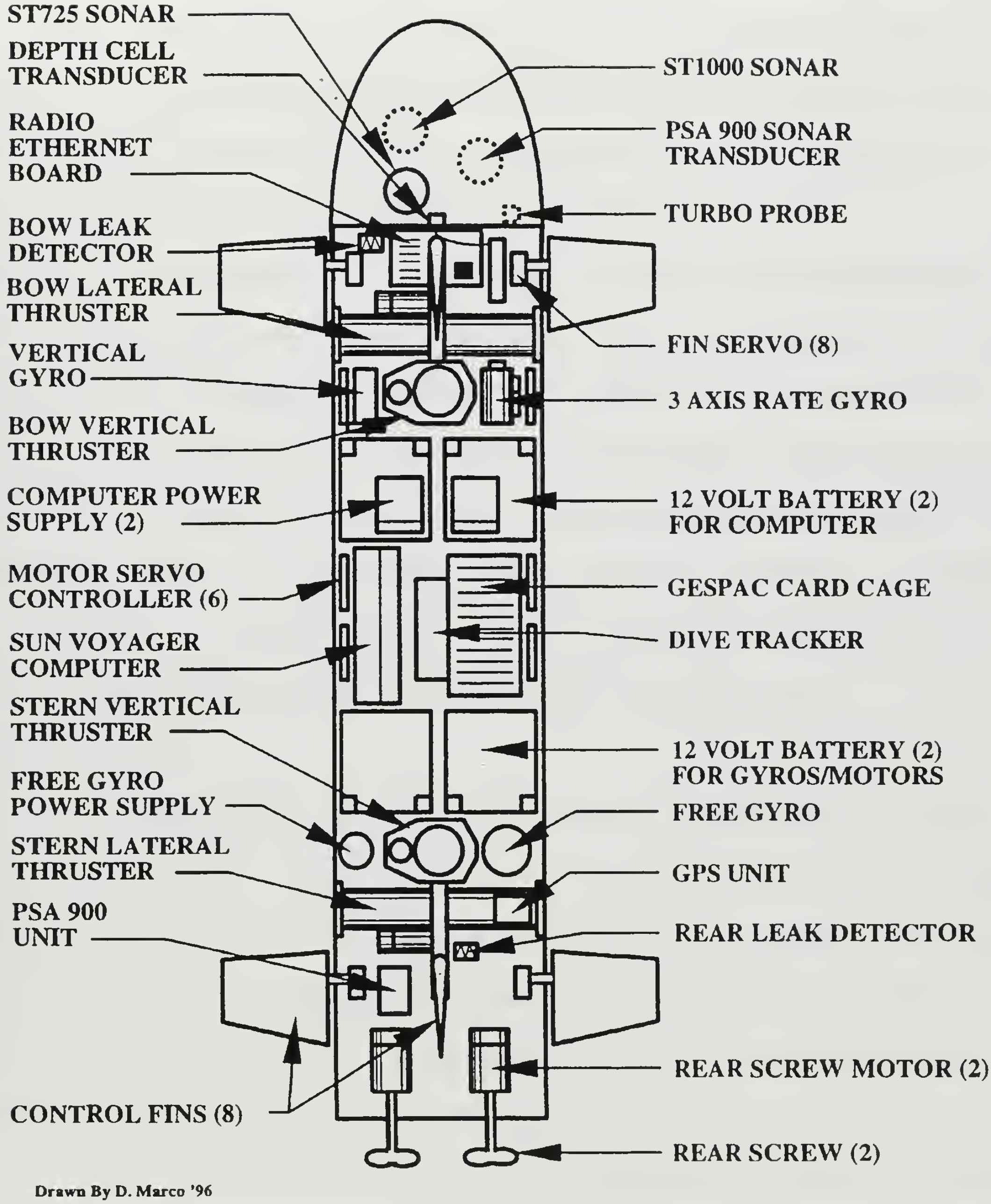

Figure 2. Internal View of *Phoenix* AUV. *DiveTracker* module is in the center. From [Marco].

III. VEHICLE NAVIGATION AND COMMUNICATION SYSTEM

A. OVERVIEW

As a survey vehicle required to run accurate search paths, the underwater navigation data *Phoenix* requires must be unusually precise and, as mentioned, updated frequently. Once a mine or mine-like object is located, it is additionally important to be able to accurately record its position so that, should it be necessary for another vehicle or perhaps a swimmer to return and destroy it, it may be easily reacquired. In keeping with the overriding goal of absolutely minimum vehicle cost while maintaining "high-tech" capability, the *DiveTracker* system (produced by Desert Star Systems in Moss Landing, California) was obtained to provide both acoustic navigation and vehicle-base communication.

As a navigation system *DiveTracker* employs a minimum of three transducers, one of which is mounted externally on the vehicle. The other two form a baseline at a known location. Using programmed pinging protocols and knowing the speed of sound in water, accurate navigation to within centimeters, through triangulation, can be obtained.

An additional feature of the *DiveTracker* system is the capability for communication. A finite set of preprogrammed messages may be sent by the vehicle or the "Surface Station," at any time, or between multiple underwater vehicles. A two digit code associated with the desired message is transmitted and, if correctly received, an acknowledgment is sent back by the receiving station. This procedure takes place by temporarily interrupting the navigation sequence, performing the communication, and then returning to navigation mode.

The system also has the ability to transmit data from a sensor onboard the vehicle as part of the navigation telemetry, thereby providing updates of sensor data at the navigation frequency of roughly a second or two in good conditions. Such a sensor might be monitoring, for example, vehicle depth, internal air pressure, leaks, or battery status.

B. *DIVETRACKER* HARDWARE

1. Transducers

DiveTracker transducers, one of which is shown in Figure (3), are active in a frequency range of 33 to 41 kHz. In terms of sound pressure level they are rated at greater than 169 dB (reference one micro Pascal per watt at one meter). The transmit voltage response is specified as greater than 136 dB (reference one micro Pascal per volt at one meter).

Consider the transducer to be pointing up when the PVC support disk, which can be seen in Figure (3), is just below the active element. Somewhat surprisingly the beam is undiminished directly up, as can be seen in Figure (4). This disk appears to restrict the beam directly down, but may act as a mirror of sorts to slightly accentuate it just below the horizontal [Flagg]. At a -3 dB reference level, the beam can be considered to run from 30 degrees below the horizontal to 90 degrees above it. In the horizontal plane the transducer is omni-directional. (Thus if the vehicle is operating at depths considerably below that of the baseline transducers, it makes sense to mount the transducer on top of the vehicle and pointing up. Conversely, a bottom mounting could be used is the baseline transducers were on the ocean floor.)

2. Vehicle Module DT1-MOD

The heart of the *DiveTracker* system is a programmable microprocessor which, together with associated electronics, is used to control the transducer(s). Mounted together they make up an "electronics module."

The vehicle has one transducer mounted externally and the associated electronics module (designated *DT1-MOD* by the manufacturer) mounted inside, as can be seen in Figures (1) and (2). The module has three primary connections: one for the transducer, one for the serial port, and one for power. The serial port enables *DiveTracker* software to be downloaded into the module and also enables the module to communicate with the vehicle's onboard computers during a mission. (In the current configuration, the GESPAC M68030 processor reads *DiveTracker* data.) Normally this consists of providing range data (raw distances from the two transducers that form the baseline) which is then processed by the vehicle's own navigation program. As previously described, however, this one-way data stream is interrupted for communication purposes, which may go in both directions, either to or from the vehicle.

3. Short Baseline Setup

One option is to configure the baseline with two transducers, each with its own electronics module. This would be required if they were separated by a very long distance in a so-called "long baseline" configuration. Alternatively, both transducers may both be controlled by one module in a "short baseline" configuration. This latter configuration was primarily used in the experimental portion of this thesis, the module (designated *DT1-DRY* by the manufacturer) being housed in a plastic box with connections for power, two transducers, and a serial port. The serial port connects the module to an IBM compatible personal computer. Together the transducers, DT1-DRY module and computer make up the Surface Station.

The computer serves several functions. Primarily it provides a radar-style display of the mission area, as shown in Figure (5). The baseline transducers are shown in the center and the vehicle position is displayed relatively along with a readout of current range and bearing. The computer also provides the user interface necessary for sending and receiving messages and provides appropriate displays at the lower right and bottom of the screen.

Also shown on the computer's display is the time since the last position update (in the upper right as "Fix:"). When messages are being transmitted, this time increases until an acknowledgment is received or the message is aborted, whereupon the system returns to navigation mode once again. If the vehicle moves beyond the system's range, and position data is no longer being received, this counter serves as the operator's clue to that fact. Since the same equipment is used for navigation or communication, if navigation is not possible, the ability to communicate is lost as well.

4. Long Baseline Setups

At greater ranges, the increased accuracy of a long baseline configuration becomes desirable. One way to achieve this is to use the DT1-DRY and Surface Station computer with only one transducer. Then, a second transducer is plugged into a second electronics module, housed in its own waterproof case and hung from a buoy at any suitable distance from the Surface Station. This comprises a Remote Station (designated *DT1-R-S*). In this way a baseline of virtually any desired length may be obtained (limited, of course, by the acoustic transmission distance).

In an actual minehunting scenario the monitoring capabilities of the Surface Station might not be needed or practical, especially if the covert nature of the mapping mission was especially important. Under these conditions the PC and DT1-DRY might be replaced by two Remote Stations. In this configuration, the baseline and all electronics would be completely below the surface (the supporting buoys need not be on the surface), providing a long baseline configuration.

An alternative to two Remote Stations would be to use two Remote Baseline Units (designated *RBS-2*). A Remote Baseline Unit is essentially a standard electronics module housed in a waterproof aluminum tube with an integral transducer. It is considerably larger than a Remote Station because it has much greater battery capacity and therefore longer life. It may also be fitted with a GPS antenna that pierces the surface so that global geographic location may be incorporated in vehicle navigation.

In the ultimate arrangement, one of the units might also be fitted with a radio and antenna and a connection to the electronics module. In this way a ship or other monitoring unit could stand off at considerable distance and, using LPI communications, still be able to communicate with one or multiple AUVs.

5. Diver Station DS-1

As a system designed initially for scuba divers, there is also a *DiveTracker* module that can be used underwater by a diver. This module (designated *DS-1*), shown in Figure (6), has a keypad that is actuated by a magnetic pointer, an LCD display, and is watertight to depths of 1000 feet. It has connections for a single transducer and a serial port for connection to a PC that is, of course, capped when the unit is being used underwater. Rather than use the module mounted in the *Phoenix* for the testing associated with this thesis, this diver unit was used. This greatly simplified the testing procedure by obviating the need to actually transport the vehicle to and operate it at the test sites, or interface with the vehicle's computers in real time.

6. Hardware Summary and Terminology

It can be seen that in the *DiveTracker* system the same basic electronics module is used in different locations and configured appropriately. A Surface Station consists of an IBM compatible PC, a DT1-DRY (the *DiveTracker* electronics module mounted inside a plastic box), and two transducers. Such a system enables remote monitoring of an AUV (or several) and communicating with it, assuming it is fitted with a DT1-MOD and the third transducer. These components are shown in Figure (7).

As long as the distance between the baseline transducers in the water is accurately known, the Surface Station may be on a boat or ashore. A long baseline may be obtained by incorporating a Remote Station, or by using Remote Baseline Units. A *DiveTracker* electronics module mounted inside a waterproof aluminum box with a keypad, LCD display and transducer make up a "Diver Station." A Diver Station was used in this thesis in place of the electronics module mounted inside *Phoenix*. In this capacity it is sometimes referred to as the "Mobile Unit."

C. *DIVETRACKER* SOFTWARE

One of the most attractive features of the *DiveTracker* system, aside from low cost, is the ease with which specialized applications may be developed and incorporated. Unlike other instruments used by divers, *DiveTracker* may be programmed for almost any function. The hardware is all based on a common electronics module. Like a personal computer, software may be purchased or written, loaded, and run on the hardware to satisfy virtually any need.

1. DiveCode

A software application run on a *DiveTracker* system is called a "DiveCode" by the manufacturer. DiveCode is written and compiled using the "C" programming language.

Desert Star has available DiveCode to perform standard diver functions, some of which are also applicable to AUVs. Like choosing a software application on a PC, different DiveCodes may be loaded and available to the user on a *DiveTracker* module, thereby changing the function of the instrument for the job at hand.

2. DTOS

The *DiveTracker* processor uses an operating system called "DTOS" (*DiveTracker* Operating System) which is analogous to the DOS used by an IBM compatible PC. The user may at any time shift to DTOS mode just like shifting to DOS on a PC. Once in the operating system, DiveCode may be downloaded if necessary, selected and run, the clock may be set, and so forth.

3. SmartDive

"SmartDive" is the fundamental DiveCode used by divers (or AUVs) for navigating and communicating. Because the same version of SmartDive is run on all modules that provide different functions based on their location (for example, Surface Station, Remote Station or Diver Station), it must be configured for its particular use. When configured for a Diver Station, for example, it provides an interface to the LCD display and enables interaction via the magnetic pointer and keypad. When configured for the Surface Station it recognizes the number and location of baseline transducers and communicates with the PC via the serial port. SmartDive may also be configured for use without a Surface Station when Remote Baseline Units are employed or if two Remote Stations are used.

4. DiveBase

"DiveBase" is the software run on the Surface Station PC that provides the radar-style display of the mission area shown in Figure (5). In that it is not run on a *DiveTracker* module, it is not DiveCode per se; rather, it is software for a PC that is loaded and run under DOS like any other.

DiveBase is run in one of two modes: "real-time" or "replay." In real-time mode the operator may keep track of the location of one or several AUVs, and receive and send messages, all of which are recorded at the bottom of the screen together with the time and whether or not they were acknowledged by the recipient. If more than one AUV is being tracked, each may be selected in turn and displayed on the DiveBase screen to get specific information regarding its range, bearing, and speed. Additionally, if any sensor data is being transmitted as part of the navigation telemetry, this information is displayed digitally and may also be displayed graphically in a time-history plot.

If desired, any real-time mission may be recorded and played back for analysis. This is done by shifting DiveBase to replay mode and selecting from among the recorded files.

Each test run in the experimental portion of this thesis was recorded and later analyzed in this manner. Whenever a real-time mission is recorded, DiveBase also records the display configuration selected by the user as well as the "parameter" file for that particular mission. Provision is also made for recording a text mission log that will be associated and displayed with the mission whenever it is replayed.

5. divebase.par

SmartDive and DiveBase are both configured using the same "Mission Parameter File." It is typically called "divebase.par" and can be edited using the text editor in DOS or any other. Divebase.par enables setting of numerous key parameters, as well as entering the text of any desired messages. Some of the key entries in divebase.par are:

- the desired message set (up to 99 are allowed)
- communication speed and "quiet" period
- receiver gain, detection threshold, transmit power and pulse length
- type of data that is transmitted through the serial port (raw ranges, x-y grid positions, etc.)
- distance between baseline transducers, depth, and relative orientation

6. DiveTerm

Downloading of DiveCode to a DT1-DRY, Diver Station or AUV mounted module is accomplished through a utility program called "DiveTerm" that is run on an IBM compatible PC. With a serial cable connected to the module, DiveTerm presents on the PC screen a "Memory Map" of the DiveCode that is currently loaded and allows the operator to, among other things, erase it or add more. Like DiveBase, DiveTerm is software for a PC and not DiveCode.

7. Sonalyse and DT Test

When not being used for navigation and communication, a Diver Station may be used for analysis of sonar signals and ambient noise in the ocean. This is accomplished by loading and running a DiveCode called "Sonalyse." Sonalyse enables reception of signals from 0-99 kHz. Display may be across the entire frequency range or in various narrower bands as well as discrete frequencies. Sonalyse provided the capability in the testing portion of this thesis for troubleshooting communication and navigation difficulties by observing the baseline pulse and message amplitudes relative to the ambient noise level. This was further facilitated by using another DiveCode called "DT Test" which is a diagnostic routine for *DiveTracker* modules. By running DT Test on the Surface Station DT1-DRY, one of the baseline transducers may be caused to ping continuously. This signal is normally clearly visible using Sonalyse. DT Test can also be used to measure ambient noise levels, somewhat like an unsophisticated version of Sonalyse.

D. NPS EVALUATIONS COMPLETED SO FAR

Considerable work has already been completed at NPS evaluating the *DiveTracker* system for use with *Phoenix*. This work has been centered on the navigation capabilities of the system. Static tests have been conducted that proved accuracy was within a few centimeters over a 100 foot test range. Additionally it has been determined that ranges to the two baseline transducers should be converted into x-y grid coordinates and then processed through a Kalman filter, vice filtering and then converting.

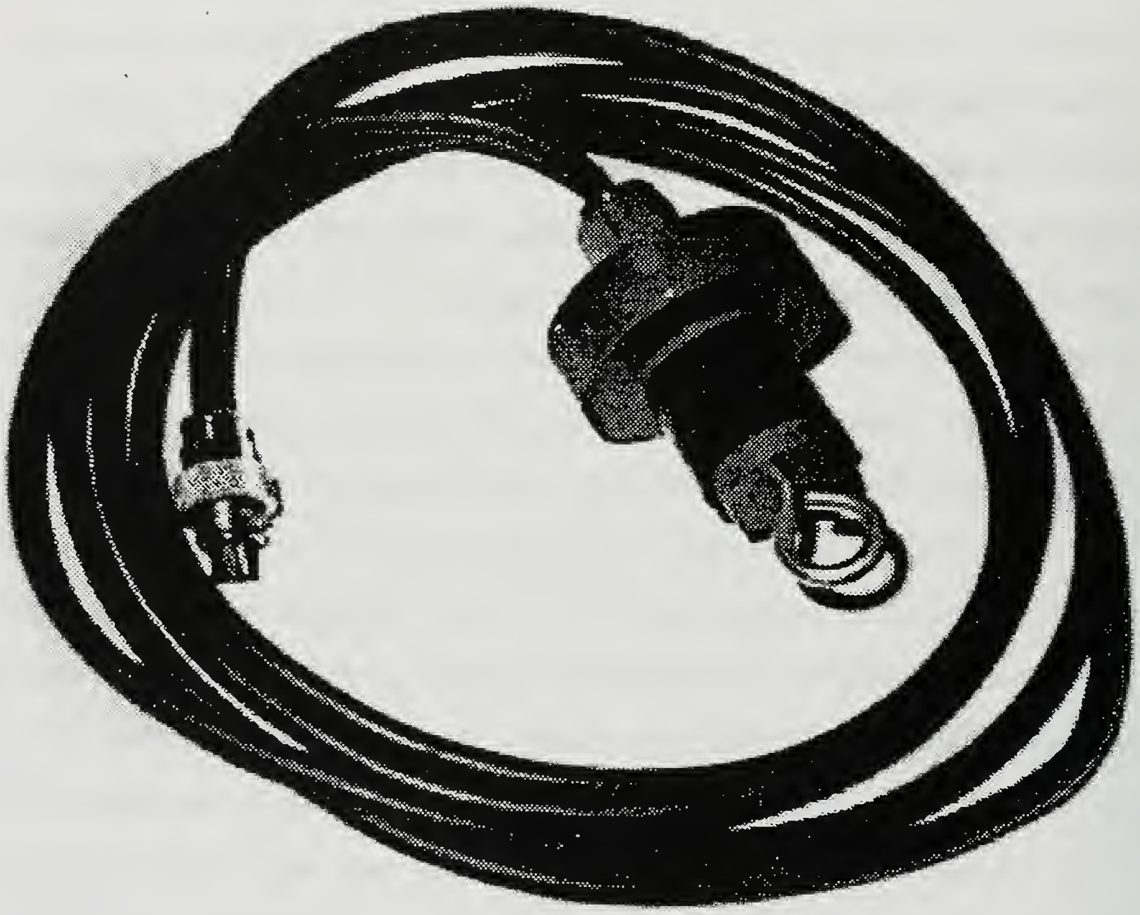

Figure 3. *DiveTracker* 40 kHz Sonar Transducer. From [Desert Star Systems].

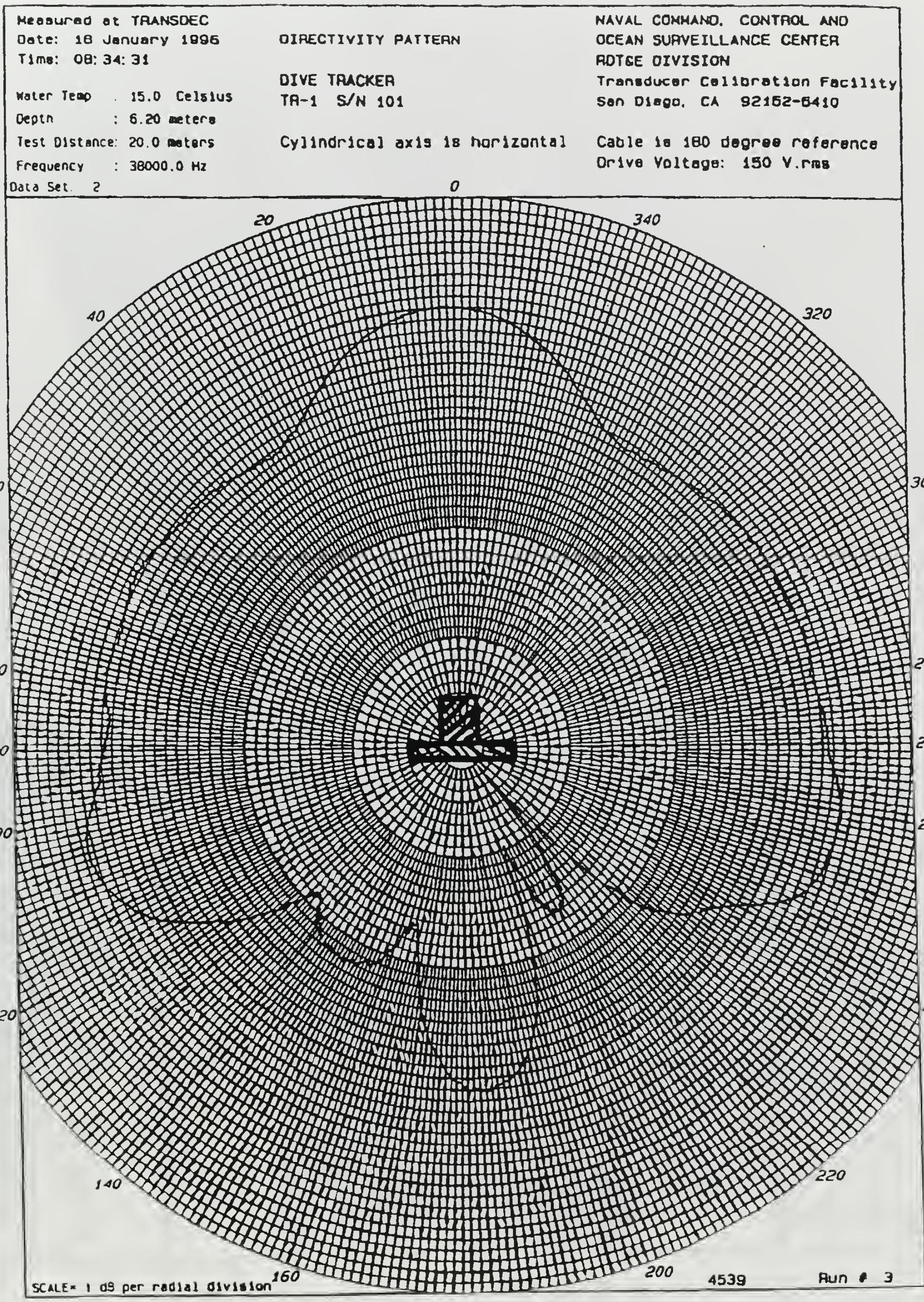

Figure 4. Transducer Beam Pattern.

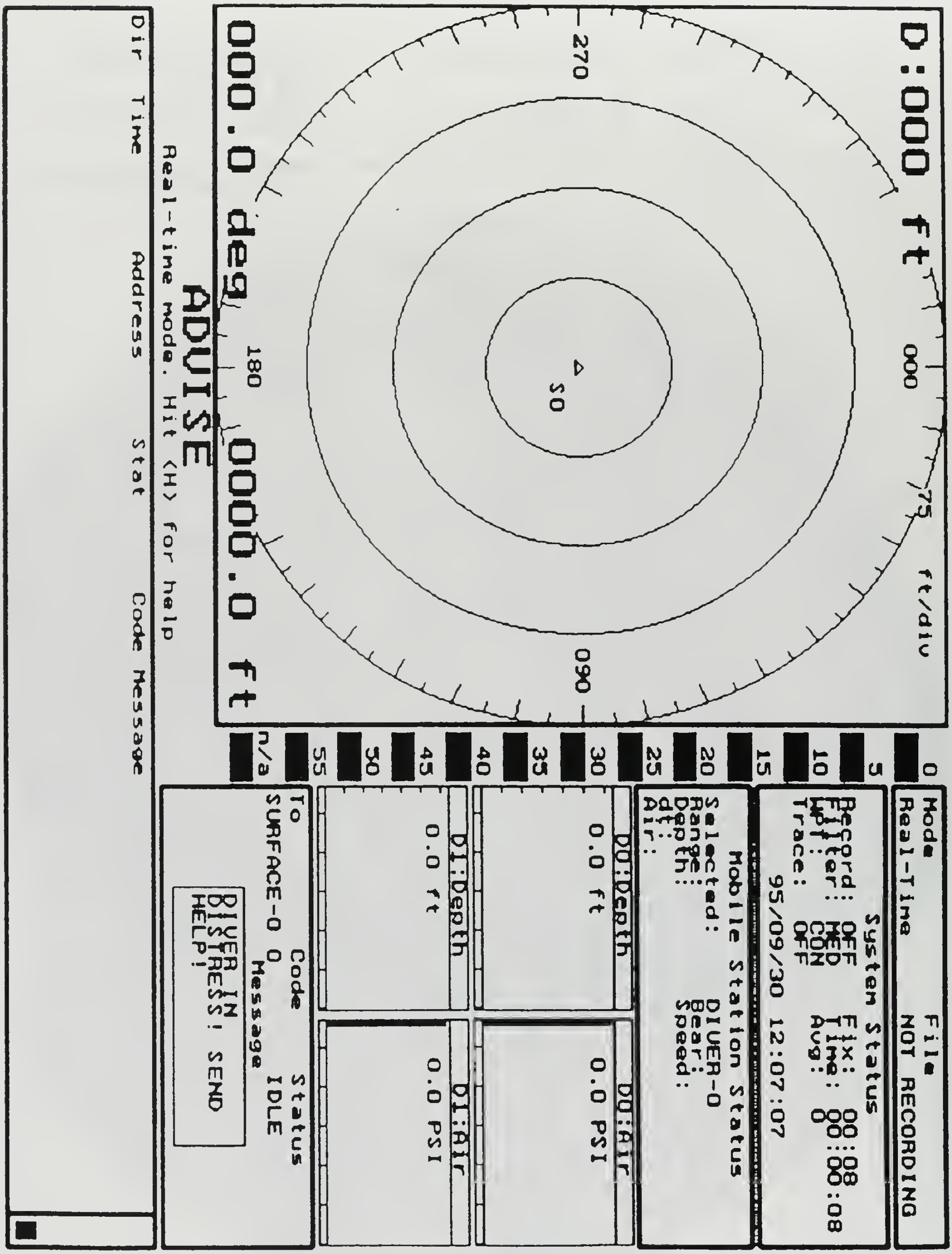

Figure 5. Surface Station Radar-Style Display. From [Desert Star Systems].

Figure 6. Diver Station DS-1 used in place of the module in *Phoenix* for testing purposes. From [Desert Star Systems].

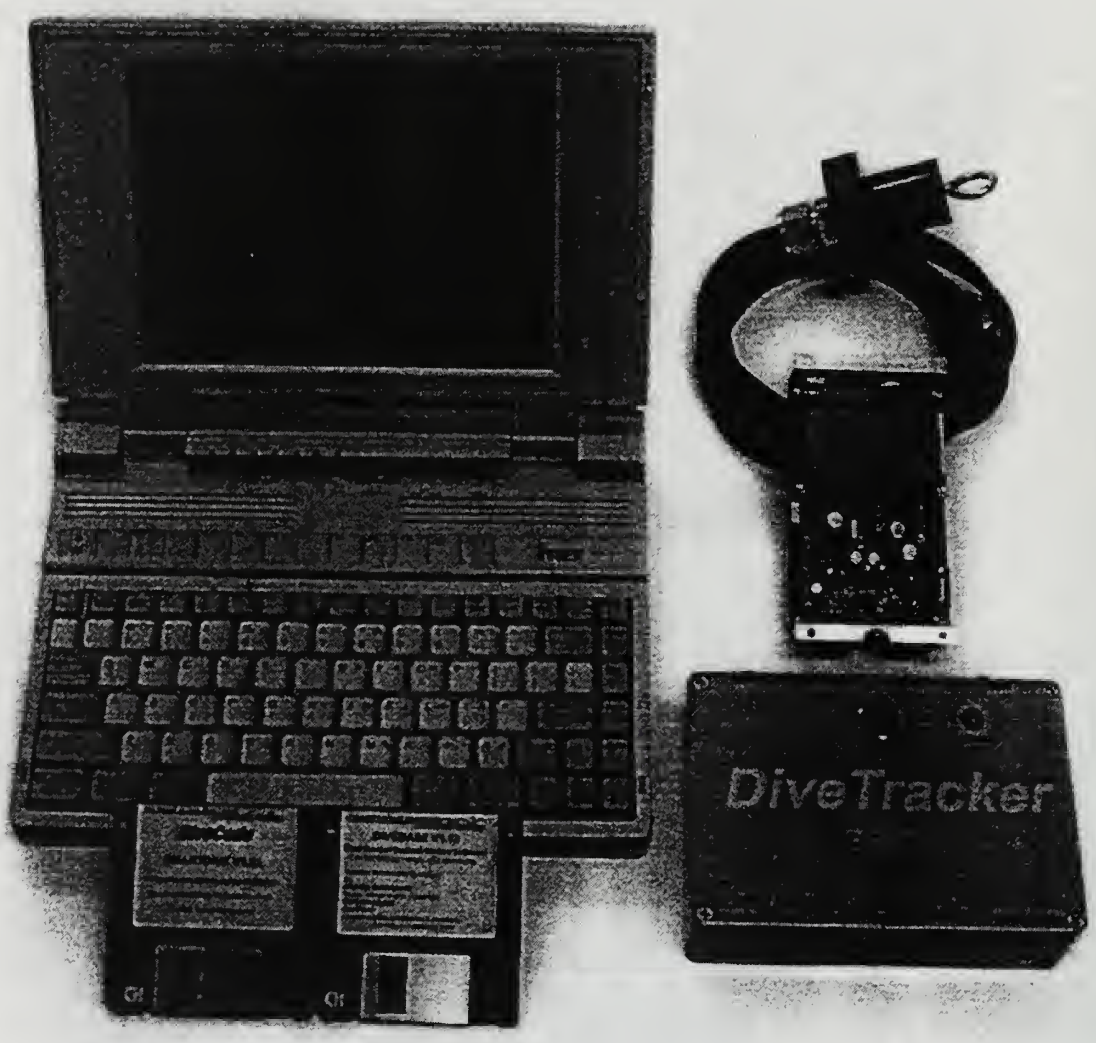

Figure 7. Surface Station computer with software, DT1-DRY electronics module, bare module for mounting in an AUV, and 40 kHz sonar transducer. From [Desert Star Systems].

IV. ACOUSTIC COMMUNICATION

A. UNDERWATER ACOUSTICS REVIEW

While various methods of communicating underwater have been theorized and often tried, they suffer from difficulties in dealing with horizontal transmission in shallow water. The field of underwater acoustics and its companion of acoustic communication present complex and extremely challenging problems. The goal here is not to solve these problems but rather to understand some of their effects on the *DiveTracker* system, especially in the shallow water, multipath environment.

1. Sound Transmission Basics

Sound in water can be thought of as a pressure wave emanating from a source that is transferred from molecule to molecule as it expands radially outward. The source for our purposes consists of a diaphragm of some sort that is caused to move very rapidly, typically by an electrical means. The receiver is also a diaphragm that moves in response to the pressure wave, generating an electrical output. Of course both source and receiver are subject to a static ambient pressure depending on the depth, so generated and received sound actually consists of a momentary difference in pressure with that of the surrounding water. Since the sound is normally generated by several movements of the source diaphragm, the pressure wave is actually a series of complex dynamic pressure variations that last for a period of time.

Many things can happen to the pressure waves between the source and receiver. Most of these result in reduction of the signal strength at the receiver end. The most predominant of these transmission losses results from spreading, which is related to the range. As the wave emanates spherically out from the source, the surface area of the sphere increases, so that the farther away the receiver is, the less the magnitude of the pressure difference between the expanding wave and the ambient. For spherical spreading, this transmission loss in dB may be calculated in decibels by taking the logarithm (base 10) of the range (in meters) and multiplying by 20.

If the sound is traveling a relatively long distance, it may be channeled within certain depths or as a result of the presence of the surface and ocean floor. Once the wave has expanded to fill the confines of the channel, it can no longer expand spherically. At this point transmission loss becomes inversely proportional to the square root of range and is a function of 10 times the logarithm of the range, due now to cylindrical spreading. The range at which spreading shifts from spherical to cylindrical is called the transition range and, in this region, the losses of the two are additive. [Coppens et al, p. 20]

In shallow water, when the pressure waves hit the surface or bottom, some of the energy is reflected into a new pressure wave (with a 180 degree phase shift) and some is effectively absorbed. The extent and nature of both is related to the sea state and type of bottom. Numerous reflected waves may combine and eventually end up at the receiver at different times, causing distortion and cancellation interference. The signal at the receiver is thus heard repeatedly, or for a longer period of time than it was generated.

The pressure wave traveling a direct path from source to receiver is also subject to absorption due simply to the viscous effects of the water. This is a linear function of range and is given by an experimentally determined absorption coefficient based on the frequency [Coppens et al, p. 22].

The underwater ocean environment is far from silent. In shallow water, ambient noise is a combination of wind noise, biologic noise, and shipping and industrial noise that is characterized primarily by its variability [Urick, p. 212-215]. The receiver has the difficult job of distinguishing the pressure wave arriving from the transmitter source from numerous other waves arriving simultaneously from other sources. The key to this problem is to set a threshold value, above which a valid signal is recognized. The problem, however, is that the higher the threshold value, the more range is restricted because of the inability to detect weaker signals. If the threshold value is too low, the system will trigger off of ambient noise. For any given set of conditions then, the threshold value is optimally set just above the ambient noise level.

The receiver may also employ amplification circuits (gain) that help a weak signal to be detected. With the right threshold value and gain, a weak signal may appear well above the ambient noise level and be easily detected. If the threshold value is too low, the ambient noise will also be amplified, potentially causing signals that might otherwise be detected to be lost. Thus it can be seen that the optimum settings of gain and threshold value are critical but need to be variable.

2. Shallow Water Challenges

Shallow water presents a unique set of challenges in the acoustic problem. Of course the surface and bottom, with their attendant complications, are never very far away. The longer the transmission path, the more likely it is that sound waves will hit the surface or bottom, making the reflective path increasingly important at longer ranges. With a hard, smooth and reflective bottom and a smooth reflective surface, the sound might even be ducted after a fashion to extend the range considerably.

On the other hand, reflections from the surface and bottom may combine destructively to greatly reduce the signal strength at the receiver [Coates]. And if the bottom is soft and absorptive, and the surface rough so that sound is scattered in many different directions with each bounce, shallow water ranges may also be significantly reduced. Finally, shallow water ambient noise may be greater due to the proximity to increased wave action, biological and man-made noise sources.

In the end, ranges in shallow water can only be said to be more variable and difficult to predict than those in deep water, and typically they are less [Flagg].

B. CURRENT RELATED RESEARCH AREAS

Past efforts at communicating underwater have recognized the time-varying nature of the underwater channel and the complexities associated with deciphering a multipath transmission. To ensure reliability frequency shift keying (FSK) has been used with time periods between pulses to allow reverberation to die down. Consequently they have been restricted to relatively low data rates. Motivated in part by the desire to explore the underwater world using remotely operated vehicles, recent research has focused on achieving higher data rates using phase-coherent modulation techniques such as phase shift keying (PSK). To overcome multipath and the time-varying nature of the acoustic channel, some of these systems employ sophisticated receivers that use multi-channel adaptive signal processing. [Stojanovic]

Still other systems retain the use of FSK but improve transmission data rate with complex signal processing algorithms [Garmer].

Recent work at Florida Atlantic University has been aimed at using Multiple Frequency Shift Key (MFSK) methods for a shallow water acoustic modem [LeBlanc et al, AUV 1996]. While these techniques may well result in the realization of a long-term goal to provide real-time underwater video transmission acoustically from an untethered vehicle, such systems are not yet suitable for a vehicle such as *Phoenix* where low power and cost requirements are paramount. Certainly from a design point of view the *DiveTracker* system offers simplicity and proven technology to meet these goals.

V. *DIVETRACKER* ACOUSTIC COMMUNICATION SYSTEM

A. MESSAGE ENCODING

A message sent using the *DiveTracker* system is encoded as a single data packet with 20 bits of information. Of these 20 bits, eight are data, four are checksum, four are address and four are command code.

Figure (8) is a graphic representation of a message. The first ping, at 34 kHz, serves as a synchronization ping and establishes the time frame origin. The remaining five pings, that carry four bits of information each, are "pulse position coded." (Pulse position coding was chosen for the *DiveTracker* system because it is a very energy efficient way of coding--20 bits can be sent in just 6 pulses [Flagg].) This means that there is a specific window of fixed size (time) in which each ping must occur. Each window is further divided into 16 subwindows. The exact time or position of the ping--the subwindow in which it falls--determines its meaning. This is the binary equivalent of 0000 to 1111, 0000 being the first subwindow, 0001 being the second, and so on. The net result is that five, four bit binary values are established at the receiver.

B. COMMUNICATION/NAVIGATION INTERFACE

The first ping of a navigation sequence, initiated by the Surface Station, is actually two pings. They are spaced in such a way as to indicate to a receiving station that it is an interrogation for navigation purposes only. This tells the Mobile Unit that there will be no following pings that would be part of a message, and allows for addressing the navigation ping to any one of up to 16 mobile units. A series of five pings back and forth follow that establish the Mobile Unit's range from each of the baseline transducers.

If the Mobile Unit is originating a message, it sends back a character on one of its navigation replies that indicates that it has a message waiting to be transmitted. The Surface Station, upon receiving this information, sends a special character back that tells the Mobile Unit to send the message, whereupon the navigation sequence stops and the Surface Station waits. There is a timeout that causes navigation to be reinitiated if no message is subsequently received.

If the Surface Station wants to send a message, it simply transmits the six required pings when the operator pushes the transmit key.

C. SYSTEM SOLUTIONS TO ACOUSTIC PROBLEMS

From an acoustic point of view, a ping may reach its destination by traveling any one of many paths. As previously described, this may cause variations in the arrival time, causing the ping to be heard more than once.

Additionally, the environment may foster the development of echoes, again causing the ping to be heard repeatedly. To combat these problems only the first ping arriving at the receiver is considered valid. Then, to allow multiple pings and echoes on the same frequency to die down, each window is followed by a "recovery period" during which the transmitter is quiet.

In an effort to improve reliability further, different frequencies are used. The synchronization ping for a message packet is always at 34 kHz, but the second ping will be at a substantially higher frequency. In all, four frequencies are used (34, 36, 38, 40 kHz), and the sequence bounces back and forth between high and low to maximize frequency separation. By using set recovery times and different frequencies, the likelihood that any one transmitted ping will be interpreted correctly is greatly enhanced.

Since the system is in navigation mode for the vast majority of its operating time, the failure of any one navigation cycle and the bad data that results is not of particular consequence. If a range is missing altogether the cycle is repeated immediately anyway, so no corrective action is required. If the range is inaccurate, it can be filtered out against other ranges on a logical basis.

Conversely, communication is carried out infrequently, and message accuracy and acknowledgment is paramount. The software is therefore designed so that it is always known whether or not the message was accurately received.

When communication is unsuccessful, one of three things may have happened: either the ping did not get through at all, it got through but was in the wrong subwindow, or there was a noise pulse generated by some external source that was mistakenly recognized as a ping. [Flagg]

Whether or not the ping is received is a function only of its strength in relation to the threshold level set for the receiver. As previously mentioned lowering the threshold level, which is one of the parameters in divebase.par, also makes the system more susceptible to ambient noise. Additionally it increases the amount of recovery time that must be allowed for echoes to die down [Flagg]. For the tests conducted as part of this work, threshold level was set at a typical nominal value that could be expected to be acceptable in a wide variety of locations likely for a minefield mapping mission.

Of course the output power of the transmitter directly affects the signal strength at the receiver. The maximum output power of transducers, as commonly set up in the *DiveTracker* system, is 186 dB reference one micro Pascal at one meter. For the tests conducted as part of this work, this maximum value of output power was used. (Using the maximum transmit electrical power consumption figure of 60 watts RMS, energy per bit is typically about 72 millijoules.)

Perhaps due to some constructive or destructive interference, the characteristics of the onset of a ping may be changed. Under these conditions it may fall into an adjacent subwindow (the second cause of trouble). For destructive interference, the ping will move in such a way as to cause the binary value to increase. This problem might be solved by using a slower transmit speed which would result in a larger subwindow size.

The final cause of trouble, a noise pulse generated by some external source, has the effect of causing the binary value to be reduced, because it precedes the true pulse.

To combat the latter two difficulties, *DiveTracker* uses a checksum that is the inverse of the modulus of 16 of the sum of the four data nibbles that are being transmitted. This means that the checksum value will tend to move in a direction opposite to the data value for any given error type. In this way the likelihood of the checksum value being altered in a compensating way is practically zero. [Flagg]

D. COMMUNICATION SPEED AND CONSIDERATIONS

The communication speed is important because the navigation sequence is interrupted while the system is transmitting messages. When *Phoenix* is engaged in a mission, frequent navigation updates are essential. If the acoustic environment is poor, or the range large, and many attempts are required to get a message through, the time during which navigation is interrupted may be significant.

The *DiveTracker* software actually allows any one of four communication speeds to be chosen in the divebase.par text file that is used to configure the equipment. Each speed has successively shorter subwindows and recovery times as depicted in Table 1. The manufacturer recommends a

speed parameter	speed (nibbles/ sec)	speed (baud)	sub-window time (ms)	recovery time (ms)	4 bit transmit time (ms)
0	3.6	14.2	10	100	1410
1	8.9	35.7	4	40	564
2	17.9	71.4	2	20	282
3	35.7	142.8	1	10	141

Table 1. DiveTracker Communication Speeds.

setting of 1 for most applications. This setting was used in most of the testing performed as part of this work. As shown graphically in Figure (9), the differences in communication speed are significant. The timing accuracy required for higher speeds is much greater than that required for lower speeds.

The length of time it takes to communicate is not just a function of the transmit time; there are other significant factors. Considering the vagaries of the underwater acoustic environment, it is essential that a message be acknowledged when it is received correctly, and as described the *DiveTracker* system performs this function by causing the receiving unit to generate a reply that indicates message receipt. The total time to communicate, then, is the transmit time for the original message, plus the signal run time, the turn-around time at the receiving station, the transmit time for an acknowledgment, the return run time, and finally the processing time at the originating station. Signal run time for a range of 2000 feet is approximately 400 milliseconds. Message transmit time at speed 1 is 564 milliseconds. If an acknowledgment is not received by the transmitting station, the software causes the message to be retransmitted up to nine times before finally giving up altogether.

E. IMPLEMENTATION IN PHOENIX

Testing of the *DiveTracker* communication system in *Phoenix* has not yet been accomplished. To do so requires some minor modifications to the vehicle's program file entitled "div_trac.c" which would enable it to recognize a message amidst a string of range values.

While messages were being sent between the Surface Station and Diver Station (DS-1) as part of the testing in conjunction with this thesis, the Diver Station's serial port was connected to a PC and the data recorded. An example of this data is presented in Figure (10). This is the same data that the computer in *Phoenix* would see from the serial port of the *DiveTracker* module it has mounted inside. Ranges strings are preceded by "~Ri:" and messages are preceded by "~M:" For *Phoenix* to be able to read an incoming message requires only that it recognize this difference.

To generate messages, *Phoenix* need only write to the serial port connected to the *DiveTracker* module. Specifically, a four byte binary pattern is required. The first byte indicates that what follows is a message, the second identifies the destination, the third identifies the originator (*Phoenix*), and the fourth is the actual data byte.

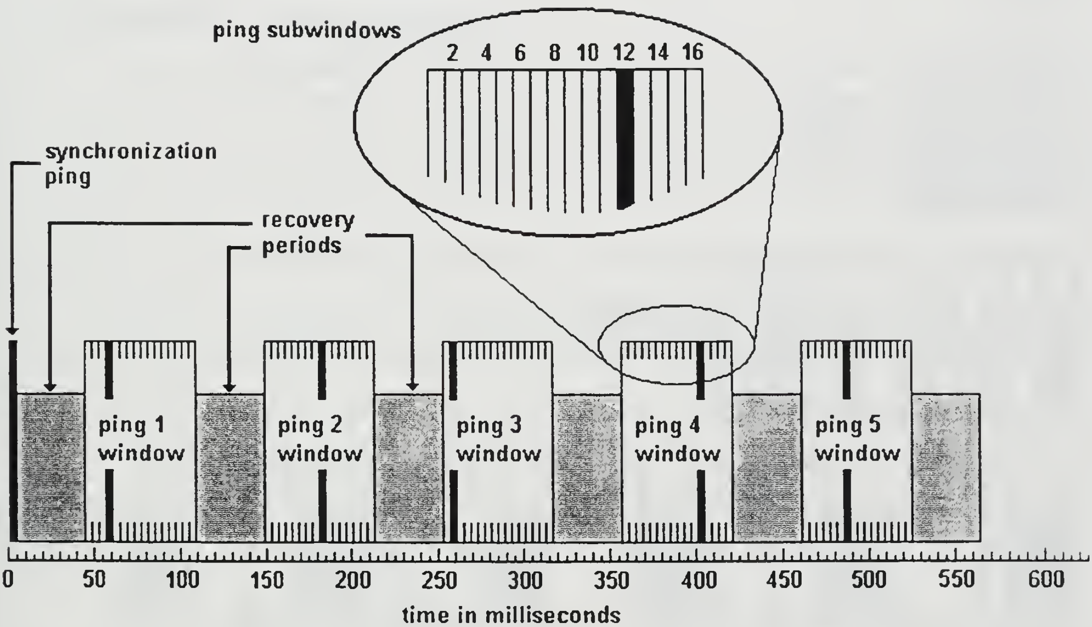

Figure 8. Message Encoding System.

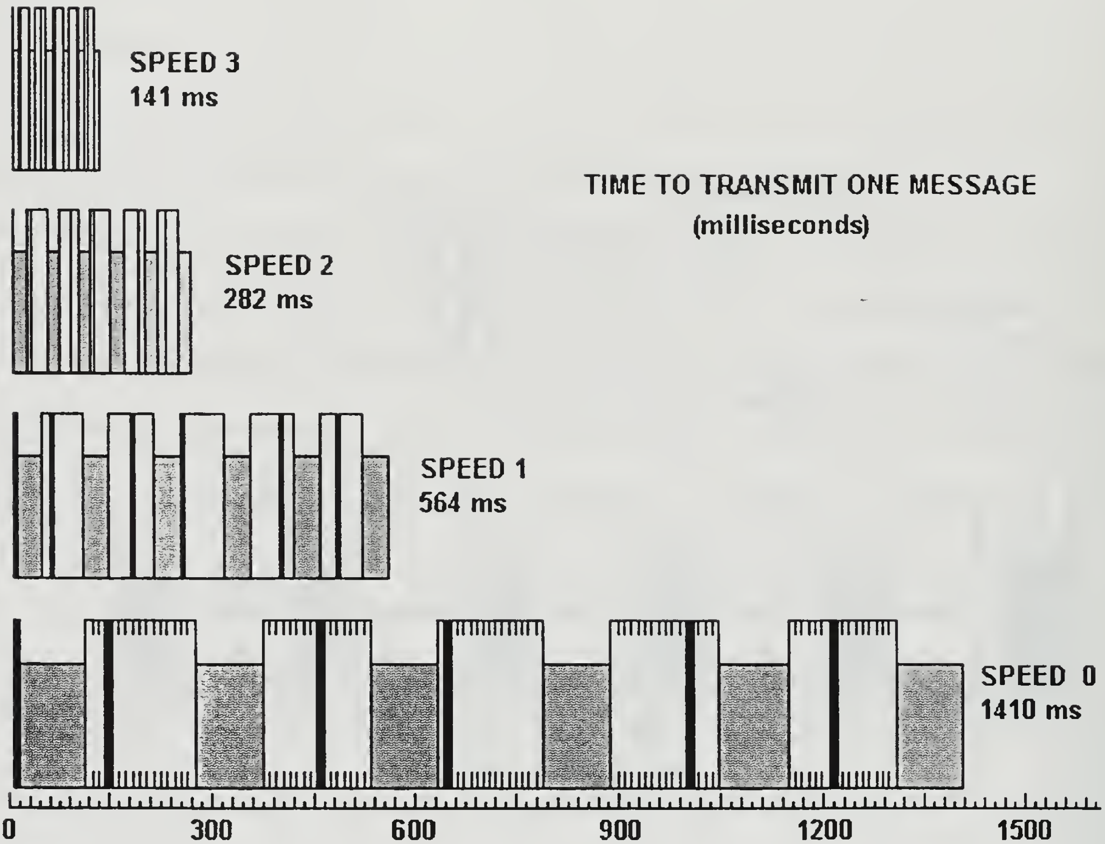

Figure 9. Communication Speed Comparison.

```
~Ri:00000331;00082435;-0000037;-0000037;-0000037;00000000
~Ri:00000337;00111207;-0000037;-0000037;-0000037;00000000
~Ri:00000336;00000390;-0000037;-0000037;-0000037;00000000
~M:0000;0006
~Ri:00000337;00111022;-0000037;-0000037;-0000037;00000000
~Ri:00000332;00000387;-0000037;-0000037;-0000037;00000000
~Ri:00000340;00114729;-0000037;-0000037;-0000037;00000000
~Ri:00000335;00000399;-0000037;-0000037;-0000037;00000000
~Ri:00000333;00085874;-0000037;-0000037;-0000037;00000000
~Ri:00000339;00000376;-0000037;-0000037;-0000037;00000000
~M:0000;0004
~Ri:00000338;00085696;-0000037;-0000037;-0000037;00000000
~M:0000;0005
~Ri:00000340;00112929;-0000037;-0000037;-0000037;00000000
~Ri:00000336;00000393;-0000037;-0000037;-0000037;00000000
~M:0000;0009
~Ri:00000335;00113324;-0000037;-0000037;-0000037;00000000
~Ri:00000334;00000395;-0000037;-0000037;-0000037;00000000
~Ri:00000334;00901171;-0000037;-0000037;-0000037;00000000
~Ri:00000341;00000387;-0000037;-0000037;-0000037;00000000
~Ri:00000338;00000390;-0000037;-0000037;-0000037;00000000
~M:0000;0010
~Ri:00000337;00527179;-0000037;-0000037;-0000037;00000000
```

Figure 10. Messages Imbedded in Serial Port Range Data.

VI. EXPERIMENTAL RESULTS AND DISCUSSION

A. OVERVIEW

This chapter deals with experimental work performed in the evaluation of the *DiveTracker* communication system. Several series of experiments were conducted both in the NPS Pool and in the ocean inside and outside of the Monterey Bay harbor area. It was decided that the best means of evaluating the system would be to calculate message success probabilities. These probabilities were based on the percentage of messages received correctly (round trip including acknowledgment) out of a statistically significant number of identical messages sent at specified ranges.

B. BASIS FOR EXPERIMENTAL METHOD CHOSEN

1. Initial Work

The first work with the system was conducted in the Naval Postgraduate School's rectangular swimming pool. The Diver Station (DS-1) was used at the edges of the pool with the transducer in the water and the baseline was set up on either a long or short side of the pool. Here experience was gained with the system in general and with the results on navigation of changing the baseline position. More importantly, lessons with regard to the effects of changing parameters in the divebase.par file were learned. A swimming pool is a difficult environment for an acoustic system. Successful navigation and communication were heavily dependent upon choosing appropriate values of receiver gain, detection threshold, transmit power and pulse length.

Pool work was followed by practice in saltwater at the Coast Guard Wharf in Monterey, using the facilities of the Postgraduate School's Marina, as shown in Figure (11). Normally a baseline of approximately 100 feet was set up on the harbor side of the pier and tests were conducted in areas where sonar transmissions would not be obstructed by anchored boats. *Phoenix* was simulated by a small rowing dinghy with the Diver Station's transducer hanging over the side at a depth of about three feet.

These tests provided a qualitative feel for the relationship between communication and navigation. Sometimes the dinghy would be underway, at other times tied off to a distant pier. Messages were sent both ways, sometimes slowly, sometimes in quick succession. There was speculation on the effects of environmental conditions as they varied from day to day and on the effects of irregular influences, such as the wakes and noise frequencies of passing boats. In all, some initial insights about how best to evaluate the probability of sending successful messages were gained.

2. Determination of Method

An extremely productive meeting with Mr. Marco Flagg, the primary design engineer and owner of Desert Star Systems, resulted in a modification of the SmartDive DiveCode for experimental purposes and additionally formed the basis of Chapter V in this thesis. The code modification simply entailed reducing the number of times the system would retry transmission of a message that was not acknowledged from eight to zero. In this way it could be easily determined whether or not any particular message attempt was successful and, by keeping a count, probabilities could be determined for various ranges.

By sending one hundred messages each way (from Mobile Unit to Surface Station and Surface Station to Mobile Unit) at any specified range, reasonable probabilities could be determined based on the overall success rate of the 200 messages combined. While these probabilities would certainly vary with acoustic conditions, it was hoped that some general pattern could be found and the actual extent of the variability appreciated.

3. Site Selection

The selection of a final testing site was critical. It was desired to approximate to the maximum extent possible the most likely conditions under which *Phoenix* would be operating when mapping a minefield.

Given the shallow water design parameter for the vehicle, depth was limited to no more than 40 feet. Assuming that mines might be laid to prevent an amphibious landing, proximity to a beach suitable for such an operation was desired, with some breaking surf that was not so large as to prevent landing boats from getting through it. Since vessel traffic is typically limited or non-existent in a minefield, the absence of interfering vessels was desired as well. Good landing beaches also are normally sand with an appropriate gradient, meaning that the bottom under the minefield would similarly be predominantly sand and reasonably flat.

Happily such a location was found north of the Fisherman's Wharf (Municipal Wharf #2), also in Monterey, also shown in Figure (11). There was occasional boat traffic in the area, along with many barking seals, but their effect on experimental results was judged to be minimal. The bottom was extremely flat at a depth averaging 25 feet and was mostly sand with some mud and kelp. The pier provided what seemed to be an ideal location for setting up the baseline, outside the surf zone and with the right depth of water underneath. Transducers were placed 10 feet below the surface. The Surface Station PC and module (DT1-DRY) were operated from a van parked on the pier, with the cables extending to the transducers in the water. Accurate measurements of baseline length were easily made with a tape measure.

4. Test Vehicle Procedures

Due to the open water environment and increased distance from boat storage area to test site, a 21 foot "Boston Whaler" driven by an outboard engine was used with a Diver Station as a test vehicle. Like the rowing dinghy, the transducer was hung over the side at a depth of about three feet. While it was possible to conduct tests with the boat underway, cavitation from the boat's propeller affecting the acoustic channel and the necessity for continuous slow speed maneuvering made this impractical. Instead, the boat was anchored at various ranges from the baseline. Since *Phoenix* has a top speed of less than two knots, the fact that the boat was anchored is not deemed to have improved the message reliability measurably. This also enabled fixing the boat's range within certain bounds as limited by the swinging radius of the anchor. Based on the results of previous research in evaluating the range accuracy of the *DiveTracker* system, the indicated ranges were accepted as being more than accurate enough, especially considering other variables affecting message success. A rough average of the ranges for any particular test of 200 messages was taken as the range associated with that success rate.

5. System Parameters

Like the test site, the parameters set up in divebase.par were selected to most closely approximate the values that would be selected in an actual mission. These values, listed in Table 2, were judged to provide optimum results for most conditions under which the vehicle might be used, and were additionally appropriate to the test site.

C. PHASE ONE RESULTS AND DISCUSSION

1. Results

Over 4200 messages were sent between the Surface Station and Mobile Unit on several days selected at random in an overall time period of a month. Weather conditions varied from sunny and hot to cold and gray. Winds varied from flat calm to approximately 18 knots, with associated variations in sea state. The detection threshold was tried at a setting of 8 and a setting of 12, and the message speed was tried at settings of 0 and 1.

In general message probability varied around 90 percent out to a range of perhaps 300 feet, and then decreased with increasing range, as can be seen in Figure (12). It was discouraging to note that maximum range appeared to be about 800 feet since, to ensure some level of reliability, *Phoenix* would have to operate well within this boundary. It was also noted that no significant differences in probability

Maximum AUV range (feet) (timeout quantity):	4000
Communication speed: 0 (slowest) - 3 (fastest):	1 : 8.9 nibbles/sec (35.7 baud)
Receive-Transmit Turn-around 'quiet' period (microseconds):	125000
Receiver gain: 0 (least sensitive) - 3 (most sensitive:	2
Detection threshold: 0 (most sensitive) - 127 (least sensitive):	12
Transmit power: 0 (least power) - 127 (most power):	127
Pulse length: 0 - 9999 microseconds:	4000
Transmit 'raw' position data via serial link:	YES
Transmit X-Y-Depth position data via serial link:	NO
Transmit message data via serial link:	YES
Network type:	Dual transducer surface station
Address mode:	More than one diver station (address code inquiry)
Diver telemetry:	Diver station sends 2-channel telemetry
Navigation data availability:	Nav data is available to surface and diver stations

Table 2. "divebase.par" Parameter File Settings

could be seen as a result of changing the parameters mentioned, or as a result of differences in environmental conditions.

2. Discoveries Leading to Phase Two

It was hoped that taking signal and noise level measurements would yield some justification for these results, and Sonalyse software was purchased for this purpose. Was it simply attenuation that caused the success percentage to drop off with range, or was there some other explanation?

Of course navigation just involves the timing of travel time for pulses, so any inaccuracy would only cause an inaccuracy in the range presented. Conversely, in communication, any inaccuracy results in a checksum that does not match, and the message is counted as a failure. As a result, navigation should work at ranges beyond those expected for communication as it is a much simpler process.

Using the Sonalyse software it was found that the signal strength was excellent in comparison to the ambient noise at ranges far in excess of those where navigation or communication were successful. Previous experience indicated that navigation and communication were rarely possible much beyond 700 feet, yet at 1000 feet the signal was 28 dB above the noise, and at approximately 1800 feet it was 23 dB above the noise.

After some deliberations and testing, the manufacturer located excess leakage current from a comparator in the circuitries of both the DT1-DRY and the DS-1 that had been used for all prior experiments. Inputs to the comparator are the received sonar signal and a reference voltage set as a function of the chosen detection threshold value. The leakage current, directed through a resistor, caused an offset voltage that affected the threshold value, effectively raising it from 8 to about 38 and causing the unit to trigger off the distorted back side of the pulse rather than the front. Repair involved replacing a 330K ohm resistor with a 10K ohm resistor which allowed more of the leakage current to go to ground, thereby reducing the voltage drop over the resistor and returning the effective threshold value to the desired level. It was anticipated that this change would significantly improve the ranges that had been seen up to that point, perhaps three or four times.

D. PHASE TWO RESULTS AND DISCUSSION

1. Results and Acoustic Channel Variability

Two days of testing were conducted with the repaired hardware. On the first day, only two data points were determined due to a problem with the DiveBase software on the Surface Station that was subsequently corrected. These two points, however, indicated a new curve might be established at ranges about twice what was originally achieved for any comparable probability.

On the second day three data points were determined that fell well off the curve anticipated based on the first day's results. In fact, they were even well below the curve generated before the hardware was repaired. Changing from speed 1 to speed 0 did not improve message success rate as might have been predicted. (As previously thought, and in all likelihood, speed 1 is more than slow enough for sending messages under most conditions.) Lowering the threshold setting from 12 to 6 did improve message success rate, but also made the Surface Station display apparently overly sensitive to the increased noise that would be picked up at such a low threshold level.

On a previous occasion, before the hardware was repaired, another data point was found in the same general area. Like the others, this point represented 200 messages, but since it was so far away from other points it appeared to be an anomaly. The conclusion based on these experiences is that sometimes the acoustic environment in the same location, under what appear to be similar environmental conditions, can be dramatically less favorable. The effect on the message success rate is extremely significant. In the final analysis, while probabilities may be established in a general way based on results of tests taken over a variety of conditions, on isolated occasions results may be not nearly as good. The variability of the shallow water acoustic channel can be dramatic.

2. Discoveries Leading to Phase Three

Despite an apparent two-fold improvement, results still remained below hopes and expectations. In a quest to find the reason, assistance from the manufacturer was sought. A RBS-2 transponder was set up that was programmed to send the same message every 2 seconds repeatedly. This transponder was hung from the boat at a depth of about 10 feet. Using special software on a computer set up on the pier, each failed message was analyzed to determine the nature of the failure.

Specifically, the RBS-2 sent a message consisting of the binary equivalent of the numbers 6, 7, 8, 9, 1. If the problem was attenuation, each pulse would be likely to reach the threshold just a little bit later in time, thereby causing the binary value to increase, and increasing the numbers above. If the problem was ambient noise, values could be expected to be corrupted entirely.

Both effects were observed. Six experiments were conducted from which it could be inferred that at gain 1, failed messages typically occurred when the signal failed to reach the threshold value. On the other hand, at gain 2 the ambient noise was magnified and the message was corrupted as a result. Signal and ambient noise level measurements using the DT Test software supported these conclusions.

Sonalyse readings taken from the boat were typical for the area. When the boat was brought to the immediate vicinity of the pier, however, readings confirmed that ambient noise level there was substantially above that of the outlying area. It could be seen on the Sonalyse display and the standard deviation value supported the idea that the noise was sporadic in nature, most likely due to sea life attached to the pier pilings. While this noise would not affect the success of an outgoing message, it would affect the ability of the Surface Station to accurately interpret a reply, thus driving down the message success percentages and explaining the disappointing results so far achieved.

E. PHASE THREE RESULTS AND DISCUSSION

1. Revised Testing Procedure

While the original attractions of the test site remained valid, setting up the baseline on the pier appeared to yield results that might be expected under only relatively adverse conditions. Such conditions might exist if a minefield was placed in an area of high ambient noise, such as a harbor, where an unusually high threshold might be required. Moving just a short distance away from the pier brought the ambient noise levels to much lower values. For the next set of tests, then, it was desired to have the

Surface Station and Mobile Unit operating under more typical ambient noise conditions.

With gracious assistance once again from Desert Star, the company's test boat "Makai" was brought down from Moss Landing to serve as a Surface Station that could be anchored away from the pier perhaps a mile up the coast off of Del Monte Beach. The Boston Whaler carried the RBS-2, still programmed to send the specified message every two seconds, and the Diver's Station, and anchored at various ranges from *Makai*. Tests were conducted throughout the day.

The testing procedure generally followed was to take ambient noise measurements and then signal level measurements for the RBS-2 and DS-1. These signal level measurements were made at ranges from 100 feet out to about 3300 feet (1 kilometer). At each range the RBS-2 was put in the water at a depth of 10 feet and the number of messages correctly received out of 100 was recorded. At selected ranges the DS-1 was put in the water, also at a depth of 10 feet, and the Surface Station sent 100 messages to it. This enabled some comparison of the message success rates between the two units.

2. Results

The signal strength readings between the RBS-2 and DS-1 were quite comparable, and it can be said that they are the same for practical purposes. The signal strength data points and corresponding curves for the RBS-2 are shown in Figure (13) at the three different gain settings used. The ambient noise level measurements, however, were quite a bit higher than those typically experienced a few hundred feet away from the pier, although they were typical for more open ocean environments in Desert Star's experience. The data collected at the pier then, after the equipment was repaired, may well have been not too far from reality after all; in the final analysis the ambient noise levels there roughly averaged to those in the more exposed ocean areas.

It was hoped that the success rates between the two units would be comparable, and that many more data points could be added very quickly to the ones already found for the repaired equipment. This would provide some feel for probabilities under varying conditions. It turned out, however, that the RBS-2 results varied widely from test to test. On one occasion, at a range of 2187 feet, 100 messages were sent with a one-way success rate of 85 percent. The test was immediately repeated with another series of 100 messages that yielded a success rate of 0. A third test immediately followed that gave a result of 12 percent. While considerable divergence in test results had been previously experienced with the DS-1, never had anything like this been recorded. It can only be postulated that the acoustic channel was not changing fast enough to keep up with a rate of a message every two seconds, and that for relatively prolonged periods the channel might be "open" or "closed" allowing a large number of messages, or none at all, to get through. Because of the procedures involved with sending messages between the Surface Station and DS-1, 100 messages may well have taken over 30 minutes to send and record. In this time the short-term variability of the acoustic channel may have had a chance to average out and provide more consistent results. With the RBS-2, 100 messages were sent in just 3 minutes and 20 seconds.

While the large number of new data points desired were not obtained, very good data on signal strength as a function of range enabled good comparisons with theoretically predicted values calculated using a spherical spreading model. (These curves have been overlaid through the data in Figure (13).) In general it appeared that message success probability was linearly related to the signal strength above the noise level, assuming appropriate values of gain and threshold were chosen, up to a certain saturation point. The curves shown through the data points in Figure (14) represent signal strength above noise level, translated into A/D converter units, with saturation occurring at about 500 feet for the outer curve. Transmission loss is based on a spherical spreading model with the addition of absorption as a linear function of range (using a constant appropriate for the 40 kHz frequency of the transducers). While there are but a few points on the outer curve, it does represent a starting point upon which to relate future data. The differences between the two curves, as a result of the equipment repairs that changed the threshold value, can readily be seen.

It must be remembered that success in Figure (14) is defined as the receiving unit accurately receiving the message and the sending unit receiving an acknowledgment. In actuality, then, each successful message was two messages, one each way. Each point in the figure represents at least 100 round-trip messages of this kind, and most points represent 200 messages (100 each from the Surface Station and Mobile Unit).

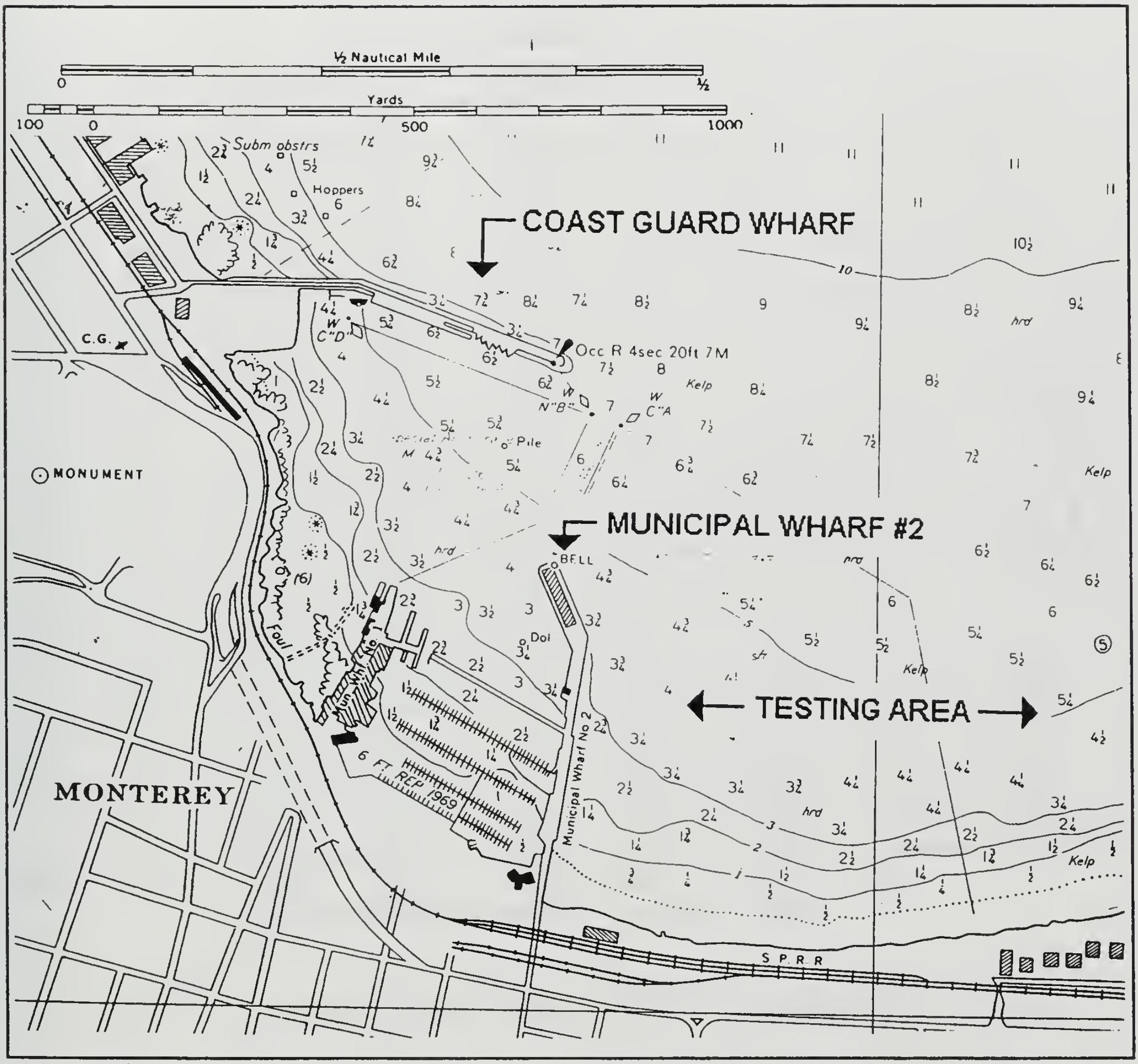

Figure 11. Testing Areas. From [C&GS Chart 5403].

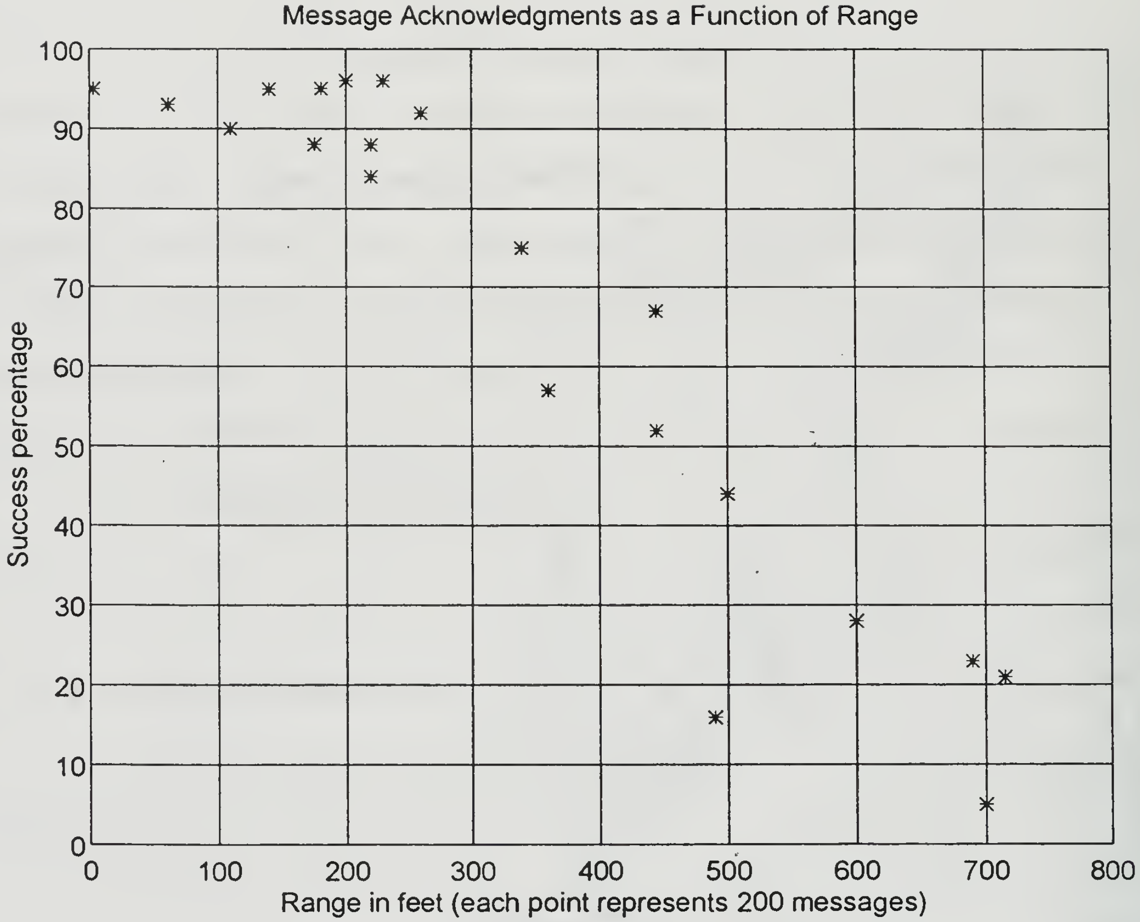

Figure 12. Phase One Test Results.

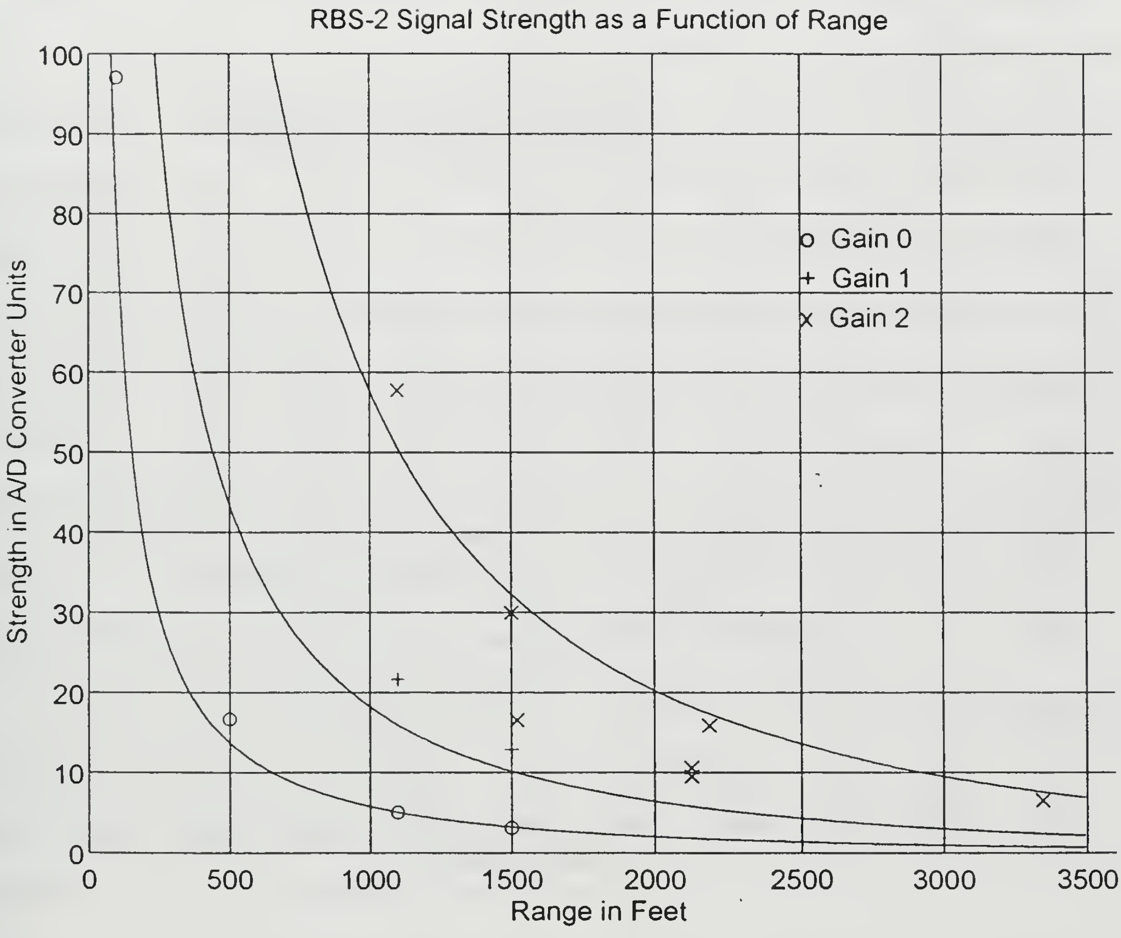

Figure 13. RBS-2 Signal Strength as a Function of Range. Similar data was obtained for the Diver Station.

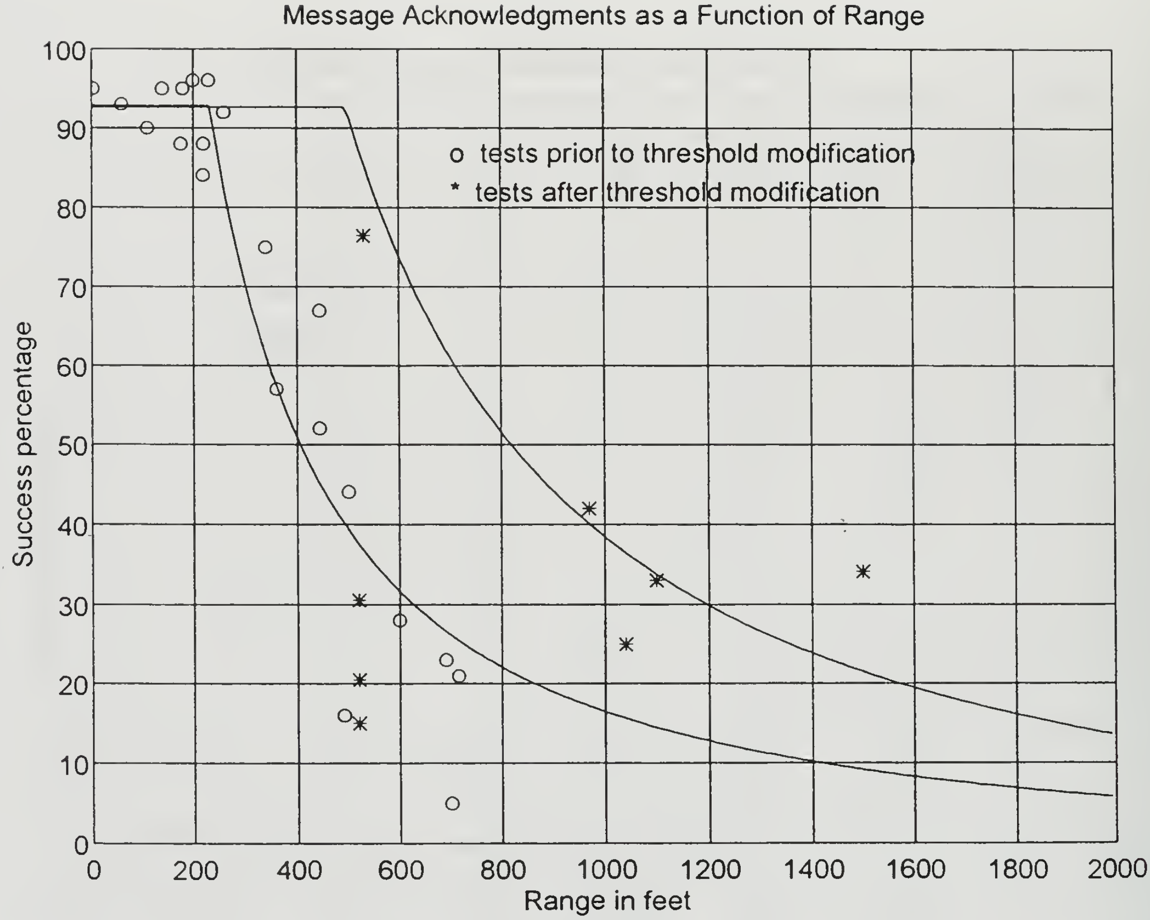

Figure 14. Message Success Probability Related to Signal Strength Above Ambient Noise Level. The curves take into consideration the modification of the threshold level based on the equipment repairs described in the text.

VII. PROBABILISTIC ANALYSIS OF RESULTS

As can be seen in the message success data records obtained with the Diver Station shown in Figure (15), the probability of any one message succeeding did not seem to have any relation to the success of the one before it. The short-term variability of the acoustic channel thus appeared to average out over the period of time it took to send the messages. It did not "open up" for brief periods of time and allow several messages to get through, thereafter "closing" and causing a whole series of following messages to fail, as was experienced at times with the RBS-2. Thus the probability of any one message succeeding was considered to be an independent trial. The probability distribution, as a result, can be considered to be binomial.

If p is the probability of success for any one message attempt, q is the probability of failure ($q = 1 - p$), n is the number of attempts, and X is the random variable, the probability distribution is given by

$$b(x;n,p) = \binom{n}{x} p^{x} q^{(n-x)} \quad x = 0,1,2,\cdots,n$$

Using this relation, Table 3 shows the probability that, in nine attempts, no message will be successful. Also shown is the probability that one or more messages will be successful, given an input probability value p. Figure (16) shows this information in graphical form.

Success probability for any one message	Probability that none succeed in 9 attempts	Probability that one or more succeeds in 9 attempts
0.1	0.3874	0.6126
0.2	0.1342	0.8658
0.3	0.0404	0.9596
0.4	0.0101	0.9899
0.5	0.0020	0.9980
0.6	0.0003	0.9997
0.7	0.0000	1.0000
0.8	0.0000	1.0000
0.9	0.0000	1.0000

Table 3. Probabilities for Sending Messages Based on 9 Attempts.

Another way of looking at the probability question is from the viewpoint of a geometric distribution, which is a special case of a negative binomial distribution. Here the random variable X is the number of the trial on which the first success occurs. The relation is:

$$g(x;p) = pq^{x-1} \quad x = 1,2,3,\cdots$$

Table 4 shows how this relation might be used. For example, assume a single message probability of 0.3, which might be associated with a range of 1200 feet from Figure (14). Using the table, 15 percent of the time 3 attempts will be required for a successful message, and 66 percent of the time success will be achieved in 3 attempts or less. Similarly, if it is desired to have, say, at least a 90 percent chance of getting a message through at 1200 feet, the software should be set to send the message up to 7 times (which would give a probability of 92 percent).

Number of Attempts	Probability	Cumulative Probability
1	0.30	0.30
2	0.21	0.51
3	0.15	0.66
4	0.10	0.76
5	0.07	0.83
6	0.05	0.88
7	0.04	0.92
8	0.02	0.94
9	0.02	0.96

Table 4. Probabilities for Sending Messages Based on an Individual Message Success Probability of 0.3.

It can be seen that, if consistent message success probability is the goal, one of the factors is range. In a general way the length of time that navigation is potentially interrupted for communication purposes may be reduced by linking the software setting for the number of message attempts to the range, using the previously described relationship.

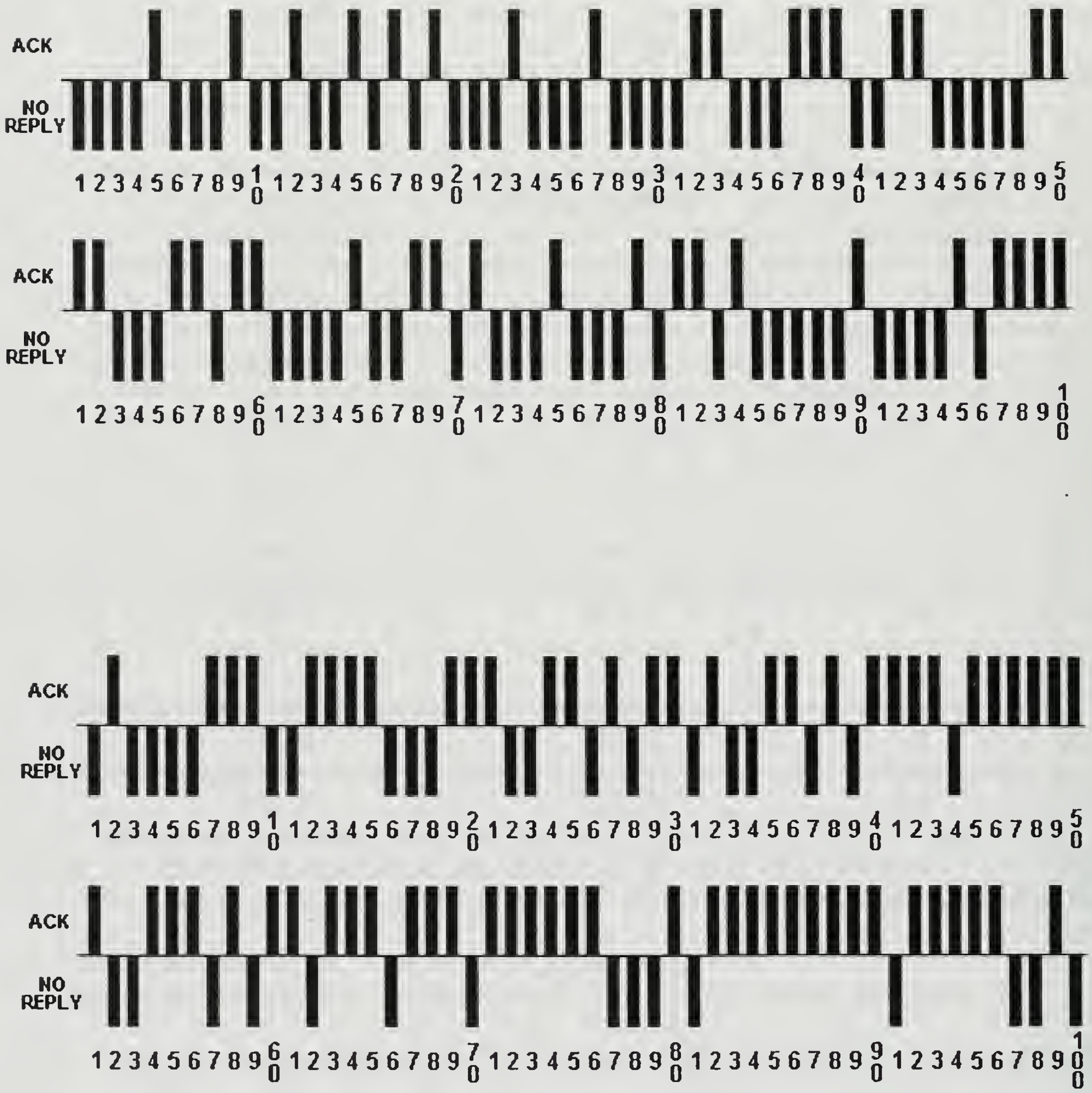

Figure 15. Typical Message Success Records at Two Different Ranges. The variability suggests that success for any one message may be treated as an independent trial.

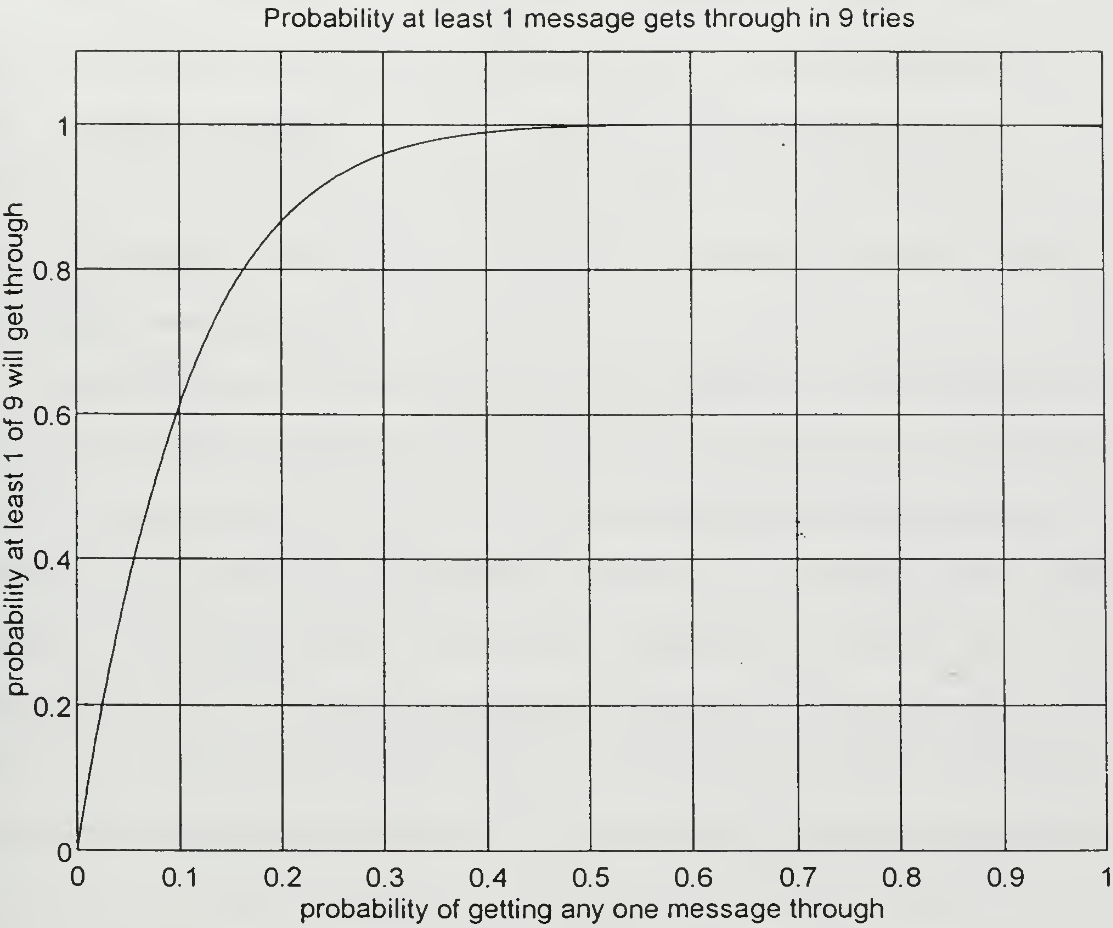

Figure 16. Single Message Probability vs. Communication Success Probability. The curve represents software set for 9 communication attempts.

VIII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Based on design, technology, reliability and method of encoding data, the *DiveTracker* system is considered more than capable of meeting the communication requirements of *Phoenix*. Its overall cost supports the vehicle's design goal of maximum capability per dollar better than any other system presently known.

Probabilities of message success based on data taken in the same general geographic area over a period of a month do follow a pattern that can be of statistical significance. The use of a spherical spreading model for transmission loss results in a curve that favorably compares to the data. Using the curve to predict message success at any given range is a reasonable approach for determining the maximum range under which a vehicle such as *Phoenix* may be expected to operate. This is based on the fact that the ability to communicate is the limiting factor in range, not the ability navigate.

The shallow water acoustic environment is challenging and more variable than might be predicted intuitively. On some days, ranges may be dramatically less than those expected. It appears that conditions during which ranges fall significantly below the predictive curve occur more frequently than conditions during which ranges fall significantly above. Viewed in another way, acoustic conditions that dramatically extend ranges do not occur very frequently, and as such cannot be considered in planned vehicle operations. On the other hand, allowance must be made for periods of significantly reduced ranges.

One very effective means of increasing the likelihood of message success is to set up the software to retry message transmission a set number of times. The value of nine used in the *DiveTracker* system seems appropriate for most conditions. It must be borne in mind, however, that nine repeated attempts at achieving a successful communication will cause the navigation sequence to be suspended for a protracted period. It may be appropriate to program *Phoenix* not to send messages during times when high navigation update frequency is especially important, or adjust the number of repeat attempts based on range.

B. RECOMMENDATIONS

It is clear from the work completed and herein described that this is only the beginning of what could be done in this area of NPS AUV research. For any follow-on researcher interested in continuing from this point, the below-described steps are recommended:

First, much more data needs to be collected at the location and under the environmental conditions of Phase 3, using the Diver Station instead of the RBS-2. This data should be collected over a time period of at least two months, at different times of the day. The more points that are found the better. Transducer depth should be introduced as another variable, to simulate varying depths under which *Phoenix* may be operating. Logistically the groundwork has already been laid.

Second, a more rigorous statistical analysis of the new data obtained should be conducted. Special emphasis should be placed on analyzing the variability of the data. In this way some idea of what can be expected under "good" and "bad" conditions can be determined. If the test area was set up with permanent buoys, so that the boat could easily go back to the same approximate locations on different days, a better set of data for determining variability could be obtained. A total of 6 buoys at 200, 400, 800, 1200, 1600 and 2000 feet would be good. A quantile range of say, 0.9, at each range, would be of interest. Two curves could then be generated, representing a range wherein 90 percent of the time, message success would be between the two parameters associated with that range.

Third, a more rigorous approach should be taken to developing the acoustic model with the hope that it will closely mirror the new data obtained. If not, discrepancies should be analyzed and corrected.

With a good model, and an empirical understanding of the variability caused by changing acoustic conditions, improvements to the system may be considered. Such improvements might include transducers that are larger, directional, operate at a lower frequency, or any combination of these things. Increasing the power to the existing transducers might also be considered. The addition of error correction codes as proposed in other work conducted at NPS also requires further development. These improvements, however, are considered less important than a more accurate evaluation of the existing equipment.

Of course actually implementing communications within *Phoenix* is a task that must be done. This initially involves only relatively minor changes in the code. There is no substitute for subsequent saltwater testing with the vehicle itself, and unforseen insights will certainly be gained in this stage. Additionally, the satisfactions of implementing a system that has real benefits remain to be had, once appropriate messages have been selected and set up for transmission at the appropriate times. These messages might include anything from status of the minehunting mission or vehicle itself, requests for further instructions or statements of intent, or inter-vehicle communications when *Phoenix* is operating with the next generation NPS AUV. Part of this includes programming the vehicle to respond to requests from the Surface Station as well.

Finally, it is recommended that the additional capabilities of the *DiveTracker* system be explored. The ability to transmit sensor data as part of the navigation telemetry, and display a time-history plot on the Surface Station display, seems to lend itself to monitoring of the vehicle's electrical status. Specifically, in combination with an "Energy Monitor" (Ample Power Company), it may be possible to continuously display battery amp-hours remaining, or time until battery depletion based on average discharge rate on the mission to that point. The usefulness of this data is obvious. The output of a depth transducer on the vehicle may also be sent as telemetry, or perhaps course and forward speed would be of interest.

APPENDIX. AN UNUSUAL PROBLEM

On one testing day in particular no navigation or communication was possible at ranges that had previously yielded excellent results. Closing the range to just a few feet did not help. Finally, by holding the mobile and baseline transducers so that their active elements were within approximately three inches of each other, contact was gained. Subsequently opening the range to three feet caused complete loss of contact.

On the previous day, the first signal and ambient noise level measurements had been taken using Sonalyse software (that had just recently been purchased). The ambient noise level measurements on the day in question were exceedingly high in comparison and it was clear that the signal was buried under the noise. No reasonable explanation could be found.

It was subsequently learned however, over a week later, that some local fisherman had been using a noise generator that was designed to keep the numerous harbor seals away! With this welcome explanation came first hand experience and the realization of how vulnerable the system is to relatively simple "jamming." A final design for use in a potentially hostile environment should keep this in mind and possibly employ some measures to overcome such difficulty, perhaps a multiple-frequency capability.

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